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A "PERMIAN" FLORA FROM THE PENNSYLVANIAN ROCKS OF KANSAS

R. C. MOORE, M. K. ELIAS, AND N. D. NEWELL
University of Kansas

ABSTRACT

Near Garnett, east-central Kansas, a thin shale that belongs near the top of the Lansing group, approximately in the middle part of the Kansas Pennsylvanian section, contains a remarkably well-preserved assemblage of land plants, terrestrial and aquatic vertebrates, and marine and terrestrial invertebrates. The flora is so strongly Permian in aspect that some paleobotanists conclude the containing beds must be of Permian age. Occurrence of a disconformity below the fossiliferous shale suggests to some students unfamiliar with the regional setting that the Garnett beds may actually be Permian, and that the apparent stratigraphic position in the Middle Pennsylvanian is due to overlap. An equally untenable hypothesis holds that the upper part of the section now classed as Pennsylvanian might be assigned to the Permian as customarily defined.

This paper shows that the fossil-bearing shale is correctly placed in the Lansing group and does not represent a Permian overlap or local channel-filling. The characters of the biota are briefly described, and peculiarities of the flora are interpreted as due to environment factors. The flora is undeniably of "Permian" type, but lived in Pennsylvanian time.

INTRODUCTION

While engaged in mapping an area in Anderson County, Kansas, during the summer of 1931, N. D. Newell found exposures of a shale that contain a remarkably well-preserved assemblage of plants associated with a scanty fauna of mingled marine and terrestrial invertebrates and vertebrates. The outcrops of this shale are located in Section 32, T. 19 S., R. 19 E., about 6 miles northwest of the city of Garnett. The geologic horizon of the deposit was originally regarded by Newell as belonging within the Stanton limestone formation of the Lansing group, Missouri series, of the Pennsylvanian section in

Kansas; and later detailed studies have substantiated this conclusion. The fossiliferous shale occurrence is of such interesting and unusual character that visits to the locality were soon made by R. C. Moore and M. K. Elias, and arrangements were made for somewhat extensive collecting of specimens. Most of the collecting was done by Mr. Elias or under his direction. Acknowledgment is due C. H. Hibbard of the museum staff of the University of Kansas for work in excavating materials at the fossil locality and in lesser degree to various others who assisted in collecting work.

The most interesting feature in connection with the fossils to be described is the decidedly "Permian" aspect of the plant assemblage. This was immediately noted by Mr. Elias, paleobotanist of the Kansas Geological Survey; and when a representative lot of the fossils was sent to the late Dr. David White, this authority on late Paleozoic floras unhesitatingly concluded that the plants in question were of Lower Permian age. Information to the effect that the horizon of the plant-bearing beds belonged at least 1,100 feet below the lowest beds previously considered as Permian in Kansas caused Dr. White to raise a question as to whether there may not exist a previously unsuspected large unconformity and overlap of the Permian on Pennsylvanian beds, and to suggest, if that is not the case, a review of evidence bearing on the possibility of lowering the Pennsylvanian-Permian boundary to a position below the Anderson County plant zone. It is the purpose of this paper to show (1) that the horizon of the plant fossils belongs to the uppermost part of the Lansing group of the Missouri series, (2) that the plant beds are of Middle Pennsylvanian age, (3) that the "Permian" aspect of the flora is explainable in terms of climatic conditions, and (4) that the occurrence cannot be assumed to indicate Permian time.

GENERAL GEOLOGIC SETTING OF THE FOSSIL-BEARING BEDS NEAR GARNETT

RAYMOND C. MOORE

The outcrops of the fossil-bearing shale described in this paper are located about 35 miles west of the eastern border of Kansas and almost exactly midway between the northern and southern state boundaries. The locality is about 75 miles southwest of Kansas

City and 50 miles due south of Lawrence. It is in the midst of the Pennsylvanian outcrop area which occupies the eastern one-fourth of Kansas. The accompanying sketch map (Fig. 1) indicates the position of the Garnett locality with reference to the areal geology of

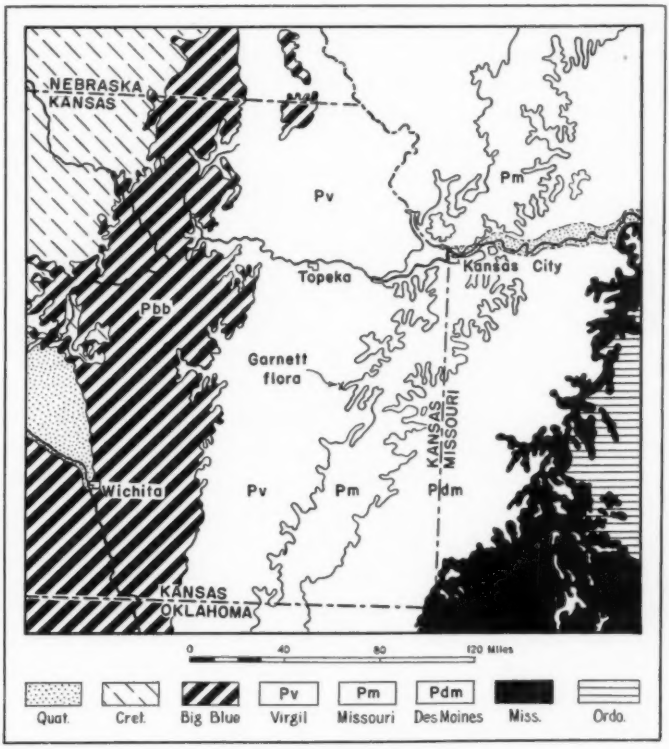

FIG. 1.—Geologic sketch map showing location of the Garnett flora

eastern Kansas and neighboring states. In this region the Pennsylvanian rocks dip gently westward and northwestward away from the Ozark uplift. The westward inclination of the strata is very uniform, except for minor local irregularities; and the dip amounts, on the average, to about 15 feet per mile. The outcrops of harder beds

are marked by east-facing escarpments, most of which are topographically distinct and easily mappable entirely across the state. There are some escarpments and local uplands made by sandstone, especially in southern Kansas. Outcrops of shale between the harder layers occur at many places along streams and in road cuts, but in general the shales form the soil- and vegetation-covered lower slopes of escarpments and the gently rolling plains areas between the successive escarpments. Most of the stratigraphic units are extremely persistent horizontally, so that it is readily possible to determine with precision the identity and stratigraphic position of different beds. Structure is simple, outcrops are numerous, and accordingly it appears that no reasonable question can be raised as to the position of beds at a given place.

The lower boundary of the Pennsylvanian rocks in the northern Mid-Continent region is marked by a prominent unconformity, the next underlying rocks ranging in age from Mississippian to pre-Cambrian. The upper boundary of the Pennsylvanian rocks has long been drawn at the horizon of the Cottonwood limestone, the conformably overlying beds being classed as Permian. In recent years evidence has been gathered pointing to existence of a widespread, but in most places obscure, disconformity, at a horizon about 200–250 feet below the Cottonwood limestone; and on the basis of paleontologic and lithologic characters this break is now defined as the boundary between Pennsylvanian and "Permian" rocks. It is believed that the "Permian" rocks of Kansas correspond in age to the Lower Rotliegende or Autunian strata of Europe; and although these rocks in Kansas and the corresponding divisions in Europe have long been classed as Permian, there are reasons for assigning them to the uppermost Carboniferous. This question does not affect consideration of the Garnett flora, except for the manner in which the base of the Permian in Europe and America has customarily been defined in recent years, i.e., on the basis of first appearance of the fern *Callipteris conferta* and of an associated flora that differs measurably from the common Upper Carboniferous floras.

On the basis of important, but not prominent, disconformities that now are widely traceable in the northern Mid-Continent area,

the Pennsylvanian section of Kansas is divided into series (Figs. 2 and 3). The lowest of these is the Des Moines series, which includes the beds from the base of the system in this region to a disconformity that occurs in the upper part of what was formerly called the Marmaton group. As formerly defined, the "Des Moines group" included beds above this break up to the conformable contact of the Bronson limestones and underlying shale. Present usage, therefore, has called for slight revision of the upper Des Moines boundary.

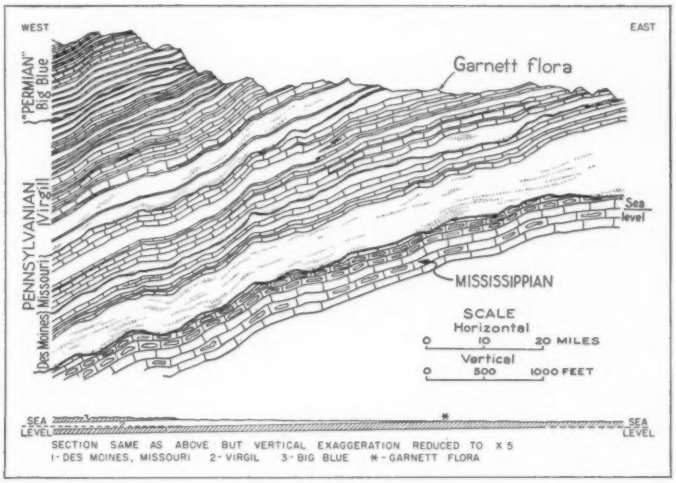

FIG. 2.—Geologic cross section from east to west in vicinity of the Garnett fossil locality. Vertical scale greatly exaggerated.

The next younger division of the Pennsylvanian rocks in Kansas is termed the Missouri series (restricted). It includes the strata from the disconformity at the top of the Des Moines, as previously noted, to a similar break that occurs near the top of the Lansing group. The Missouri series is clearly differentiated from the Des Moines on paleontologic, as well as physical, characters. The Garnett flora occurs near the top of the Missouri series; and, as indicated in the description of local geology by Newell, the disconformity at the top of the Missouri series occurs above the fossil-bearing shale.

The term "Virgil series" has been introduced to designate the

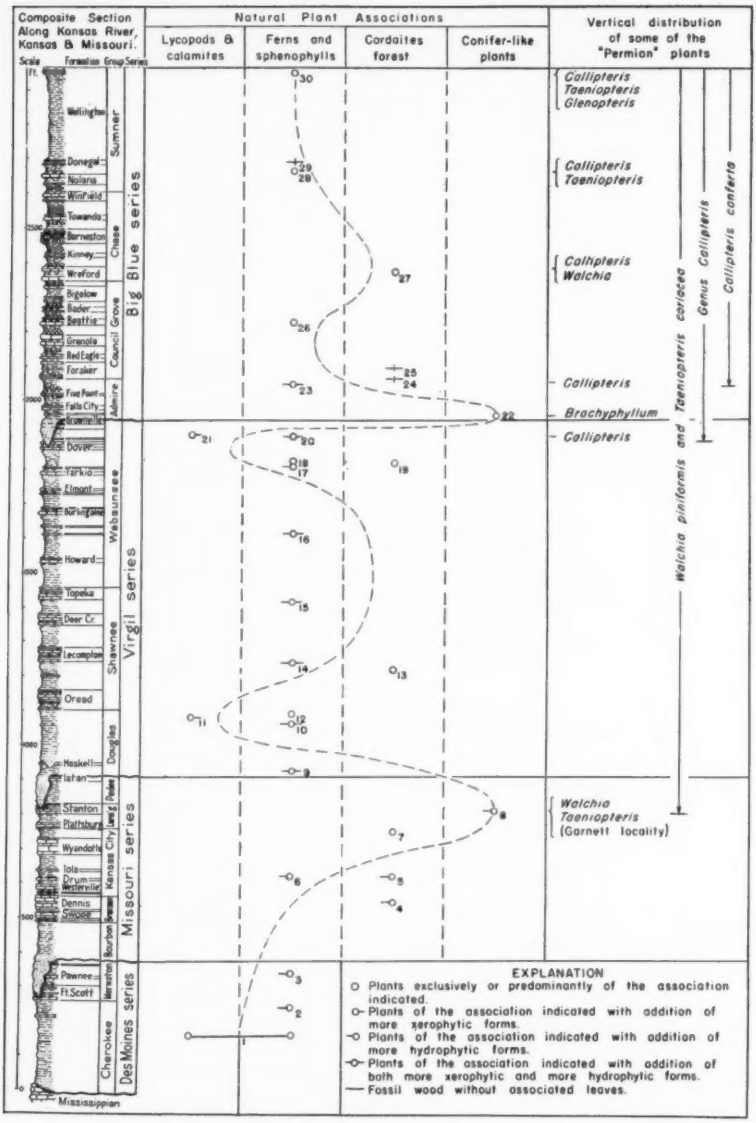

FIG. 3.—Vertical distribution of terrestrial floras in the Upper Paleozoic of Kansas and western Missouri showing climatic influences upon these floras and gradual appearance of some "Permian" plants.

strata between the disconformity at the top of the Missouri series (as restricted) and the break previously mentioned some 200 feet below the Cottonwood limestone. These rocks were formerly included in the "Missouri group," but there is now no question as to the stratigraphic importance of the break at the base of the Virgil series. It appears to be associated in origin and to correspond in time with the prominent folding of the geosynclinal area in the Arbuckle Mountain region of southern Oklahoma.

The dominantly marine strata that occur between the top of the Virgil beds and the base of the Cimarron red beds are classed as the Big Blue series. These rocks have long been regarded as Lower Permian in age; but because their proper classification is now not satisfactorily settled, they are here designated as "Permian."

In northern Arkansas, northeastern Oklahoma, and elsewhere in the Mid-Continent region there is a stratigraphically distinct and well-defined series of Pennsylvanian beds that occurs below the Des Moines series. These are the Morrow beds which rest unconformably on Upper Mississippian rocks. They are mentioned to complete the statement of Pennsylvanian major stratigraphic divisions, but do not enter into discussion of the problems of the Garnett flora.

The major stratigraphic units of the Kansas Pennsylvanian that have been designated are indicated in Figures 2 and 3, which show also the stratigraphic position of the fossil-bearing beds at Garnett. The structural, as well as the stratigraphic, relationships of the Garnett beds are shown by the geologic cross-section drawn from east to west through the Garnett region extending from the eastern boundary of the state to a point somewhat west of the lower boundary of the "Permian" rocks. The section is self-explanatory and makes reasonably evident the conclusion that the fossil-bearing shale at Garnett cannot be equivalent in age to *Callipteris*-bearing Lower "Permian" beds which outcrop some 70 miles to the west.

If we assume that the inferred stratigraphic position of the Garnett beds is somehow erroneous and that they are actually equivalent in age to some part of the Big Blue series of Kansas, it is necessary to prove first that the shale at Garnett does not underlie strata referable to the Missouri series, and that, on the other hand, it is much younger than any of the surrounding rocks of the Anderson

County area. Mr. Newell presents evidence showing that a limestone belonging to the Lansing group overlies the plant-bearing shale. If, however, the identification and stratigraphic interpretation of this overlying limestone is questioned, and if we seek to associate the Garnett beds with the apparently much higher "Permian" strata, it is necessary to assume (1) the non-deposition of Virgil strata, which have a thickness of 1,100 feet or more immediately west of this locality, followed by eastward overlap of Lower "Permian" strata, (2) erosion in pre-"Permian" time of any Virgil deposits laid down in this region, followed by eastward overlap of Lower "Permian" beds, or (3) the post-Virgil trenching of Virgil and uppermost Missouri strata by a channel a thousand feet or more in depth, the filling of this channel in Lower "Permian" time, and the subsequent removal of all traces of the channel and its filling except the bottom-most part, consisting of the fossil-bearing Garnett deposits.

As indicated by the inconsiderable changes of thickness in the Virgil series as they are traced westward underground from their outcrop, and as judged by the uniformity and thickness of various limestone units, there is every reason to conclude that originally the Virgil deposits extended a considerable but unknown distance eastward from the present outcrop belt. The structural attitude of the Lower "Permian" strata is strictly parallel to that of the underlying Virgil and older Pennsylvanian beds, except for such slight effects as are due to variations in thickness. The hypothesis of non-deposition of Virgil strata in the Garnett area or of the removal of these strata by widespread erosion in this part of Kansas in pre-Big Blue time appears to be a gratuitous assumption that is entirely unreasonable. The anomalies of the hypothetical stratigraphic and structural peculiarities that would be involved are sufficiently indicated in the diagrammatic cross-sections (Fig. 4) which represent graphically the assumed conditions.

Channel-like depressions cutting downward 100 or perhaps even 200 feet into comparatively evenly stratified Pennsylvanian deposits are known in the Mid-Continent region of the United States. No known channel deposits remotely comparable to the hypothetical 1,000-foot Garnett channel are known, and for various other reasons this suggestion may be dismissed as absurd.

Consideration of the general geologic setting of the fossil-bearing shale at Garnett indicates definitely that these beds cannot be equivalent in age to the Lower "Permian" beds which occur a thousand feet or more higher in the section. They belong where they appear to occur, in the upper middle part of the Pennsylvanian section of Kansas. On the basis of local geologic studies they are placed definitely below the disconformity that marks the lower boundary

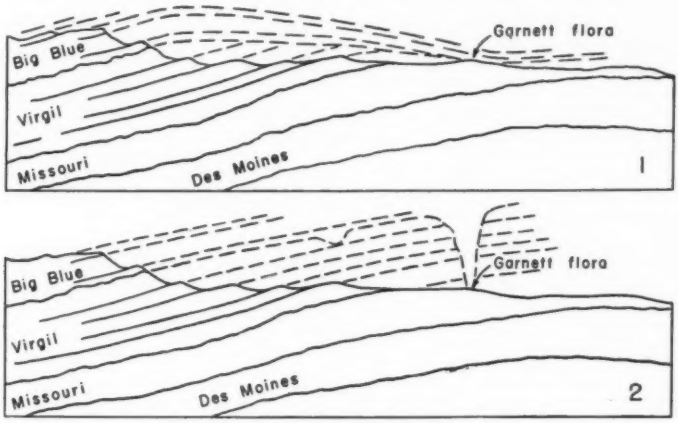

FIG. 4.—Diagrammatic geologic cross sections showing hypothetical structural and stratigraphic relationships necessary to account for an assumed equivalence in age of the Garnett fossil-bearing beds to part of the Big Blue ("Permian") series. *1* indicates overlap of Big Blue strata eastward; *2* shows hypothetical channel at base of Big Blue series cutting downward through Virgil strata. Neither of these conditions is believed reasonable.

of the Virgil series. Accordingly, if these plants indicate Permian age, all of the Virgil series and presumably, also, the Missouri series are referable to Permian time.

CHARACTER AND SIGNIFICANCE OF THE LATE PALEOZOIC FLORA AT GARNETT

MAXIM K. ELIAS

The locality at Garnett has yielded an important fossil flora. This flora is beautifully preserved, is very prolific, and, while having a general "Permian" aspect, is, to our best knowledge, found in rocks

of Middle Pennsylvanian age. This age is indicated by geologic evidence, and is also supported by evidence of some diagnostic marine invertebrates and even by remains of a few ferns and pteridosperms which are here found associated with the predominant remains of gymnosperms (*Walchia* and others).

The bulk of the flora is composed of the remains of *Walchia piniformis* (*sensu stricto*) with the addition of a few other gymnosperms, some ferns and pteridosperms, and a few other plants. With this

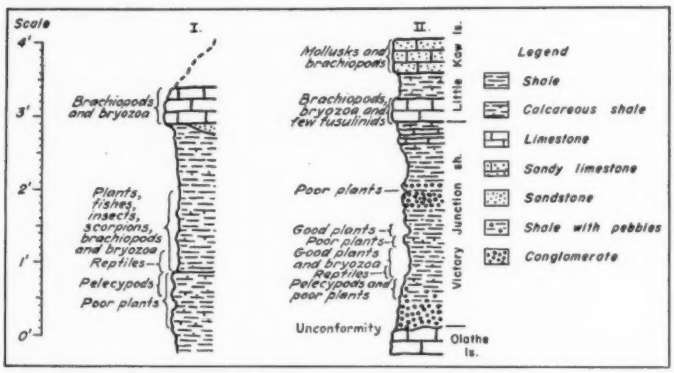

FIG. 5.—Detailed sections of the rocks at the *Walchia* locality in the vicinity of Garnett, Kansas, to show distribution of the fossils. (*I*) Section at the University of Kansas quarry. (*II*) Section in the cut on the north side of the road about 30 yards east of the quarry.

flora are also found a few insects, a scorpion, small fishes, small primitive reptiles,[1] and marine invertebrates. The exact distribution of these remains in the local rocks is shown on the accompanying detailed columnar section (Fig. 5) taken at the fossil quarry and at the best exposure in the road-cut, about 35 yards east of the quarry. Preliminary announcement of the character and significance of the flora was given by me at the 1932 meeting of the Paleontological Society.[2] One insect wing from Garnett (*Parabrodia carbonaria* Carpenter) has been described by Carpenter,[3] and the Garnett

[1] These vertebrates are under study by H. H. Lane, of the University of Kansas.

[2] *Geol. Soc. Amer., Bull. 43* (1933), abst., p. 285; also *XVI Intl. Geol. Cong., Abst. of Papers* (Washington, 1933), pp. 71–72.

[3] F. M. Carpenter, *Univ. Kansas Sci. Bull. 21* (1933), pp. 365–67.

fish remains have been described by Hibbard.[4] A beautiful large slab with two complete branches of *Walchia piniformis*, which was taken from the quarry and mounted by Mr. Hibbard and on which I found the insect wing described by Carpenter, has been illustrated by Moore in his *Historical Geology*.[5] The photographs of selected plant remains and of the scorpion (Figs. 6, 7, and 8) are published here for the first time. A complete description of the whole flora is in preparation.

Character of the flora and its age.—The accompanying list showing preliminary identifications of the plant remains collected at the Garnett locality includes practically all of the available material except a few very fragmentary and imperfect remains. In this list new generic and specific names are given only to those forms which have been already described or are here illustrated.

FLORA OF THE VICTORY JUNCTION SHALE MEMBER OF THE STANTON LIMESTONE FROM THE VICINITY OF GARNETT, KANSAS

Palaeophycus bullatus Elias, n. sp.
Paleophycus n. sp.
Annularia gallioides Lindley and Hutton (=*A. spicata* Gutbier)
Sphenopteris (*Aneimioides*) *zeilleri* Elias, n. sp.=*S. polyphylla* Zeiller, 1886, 1888, not Lindley and Hutton
Sphenopteris (*Discopteris*) cf. *goldenbergi* Andrae
Sphenopteris cf. *minutisecta* Fontain and White
Pecopteris cf. *abbreviata* Brongniart
Neuropteris fimbriata? Lesquereux, pinnule with attached seedlike body
Neuropteris (*Mixoneura*) *whitei* Elias, n. sp. (belongs to the group of *N. impar* and *N. acuminata*)
Odontopteris (*Mixoneura*) *sternbergii* mut. α Elias, n. mut.=pars. *O. obtusa* Weiss, 1869–72, Pl. III, Fig. 5 only.
Odontopteris n. sp., aff. *Neuropteris callosa* Lesquereux and *N. odontopteroides* Fontain and White
Callipteridium grandifolium Fontain and White
Alethopteris kansasensis Elias, n. sp. (belongs to *Alethopteris lonchitica* group)
Alethopteris sp. cf. *massillonis* Lesquereux
Desmopteris n. sp. A
Desmopteris n. sp. B
Taeniopteris coriacea Goeppert

[4] C. W. Hibbard, *ibid.*, pp. 279–87.

[5] R. C. Moore, *Historical Geology* (New York and London: McGraw-Hill Book Co., 1933), p. 380, Fig. 228.

Taeniopteris cf. *newberriana* Fontain and White (= *T. multinervis* Weiss)
Taeniopteris cf. *angelica* D. White
Taeniopteris n. sp.
Pteridospermostrobus stopesi Elias, n. sp.
Lepidophyllum? cf. *tumitum* Lesquereux
Cordaites n. sp., aff. *borassifolius*
Cordaites n. sp., aff. *clerci* Zalessky
Samaropsis n. sp. A
Samaropsis americana Elias, n. sp.
Samaropsis n. sp. B
Samaropsis sp.
Dicranophyllum? garnettensis Elias, n. sp.
Walchia piniformis (Schlotheim) *sensu stricto*
Walchia filiciformis Sternberg
Walchia cf. *pinnata* Gutbier
cf. *Walchia* (*Trichomanites*) *frondosa* (Goeppert)
Voltzia foliosa Elias, n. sp. cf. *liebeana* Geinitz
Ullmania? sp.
? *Lecrosia* n. sp. (or n. gen., n. sp.)
Dichophyllum moorei Elias, n. gen., n. sp.
Dichophyllum sp.

Two opinions as to the age of this flora seem to be possible. The first one is easily reached at first glance. The predominance of *Walchia piniformis*, with addition of other conifer-like remains and of *Taeniopteris*, gives the flora so striking a "Permian" aspect that if a paleobotanist were asked to determine the age without knowledge of where these plants came from, he would almost certainly conclude that the assemblage belonged to Permian time. An opinion to this effect, for instance, was unhesitatingly given in 1931 by the late Dr. David White, who wrote to me concerning this flora: "If you have found *Dicranophyllum* and *Taeniopteris* as well as several species of *Walchia* at Garnett, you will have lost a controversy as to the age of the Garnett [flora], for most European paleobotanists will regard the flora as Permian." He added: "In fact, it will not be surprising if *Callipteris* is also present in the plant-bearing beds."[6]

Indeed, of all Permian plants which are usually considered typical for this period in Europe, we have at the Garnett locality nearly every one except *Callipteris*. The point is, however, that the latter

[6] Letter of October 28, 1931.

FIG. 6, ILLUSTRATIONS 1–12.—All figures are natural size and are not retouched (except legs and claws of the scorpion). *1*, *Palaeophycus bullatus* Elias, n. sp.; *2* and *3*, *Pteridospermostrobus stopesi* Elias, n. sp. (Illus. *3* is holotype); *4*, *Neuropteris fimbriata?* Lesquereux; *5*, *Sphenopteris* (*Aneimioides*) *zeilleri* Elias, n. sp.; *6*, *Neuropteris whitei* Elias, n. sp.; *7*, *Annularia gallioides* Lindley and Hutton; *8* and *9*, *Alethopteris kansasensis* Elias, n. sp. (Illus. *8* is holotype); *10*, *Callipteridium grandifolium* Fontain and White; *11*, *Taeniopteris coriacea* Goeppert; *12*, *Mazonia hungerfordi* Elias, n. sp.

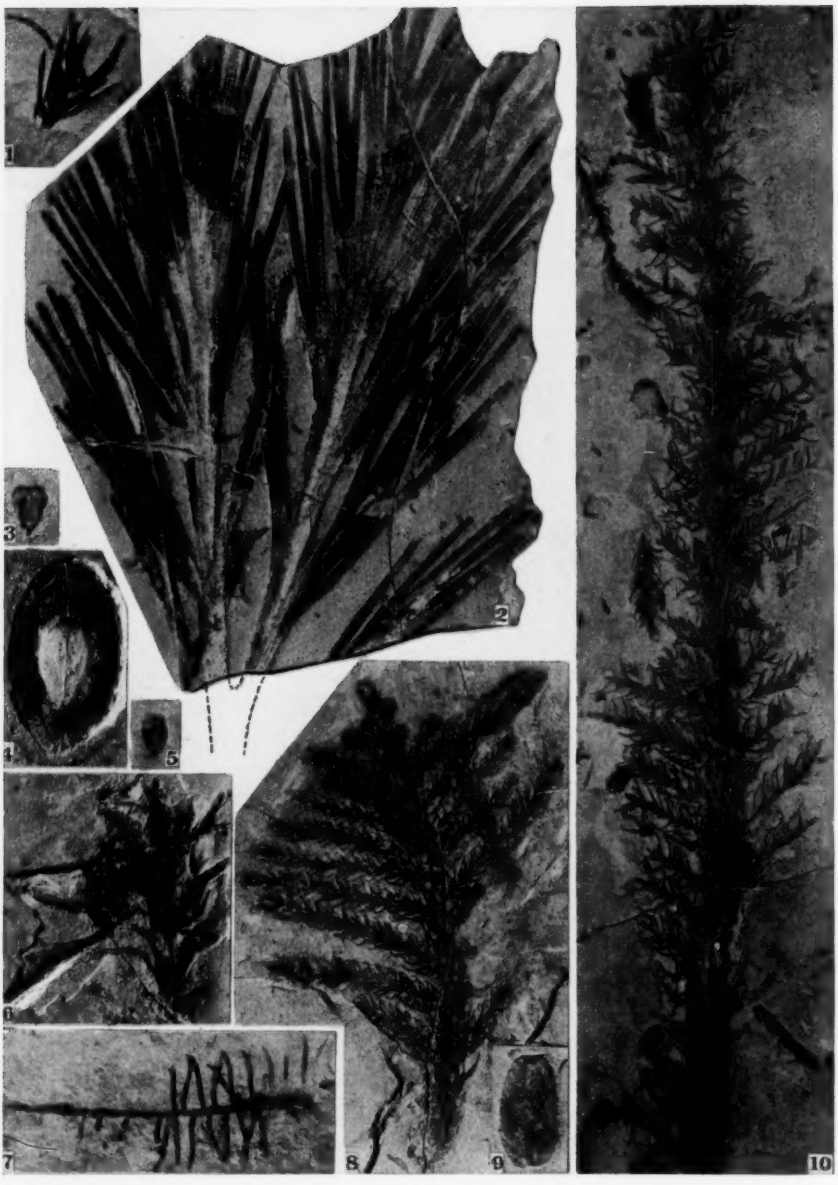

FIG. 7, ILLUSTRATIONS *1–10*.—All figures are natural size and are not retouched. *1*, *Voltzia foliosa* Elias, n. sp.; *2*, *Dichophyllum moorei* Elias, n. gen., n. sp.; *3*, *Samaropsis* n. sp. A; *4*, *Samaropsis americana* Elias, n. sp.; *5*, *Samaropsis* n. sp. B; *6*, *Dicranophyllum? garnettensis* Elias, n. sp.; *7*, cf. *Walchia* (*Trichomanites*) *frondosa* (Goeppert); *8*, *9*, and *10*, *Walchia piniformis* (Schlotheim) *s.s.* The cones of Illustrations *8* and *9* are probably male cones. Illustration *10* shows four seedlike bodies in apparent direct attachment to apices of lateral branchlets.

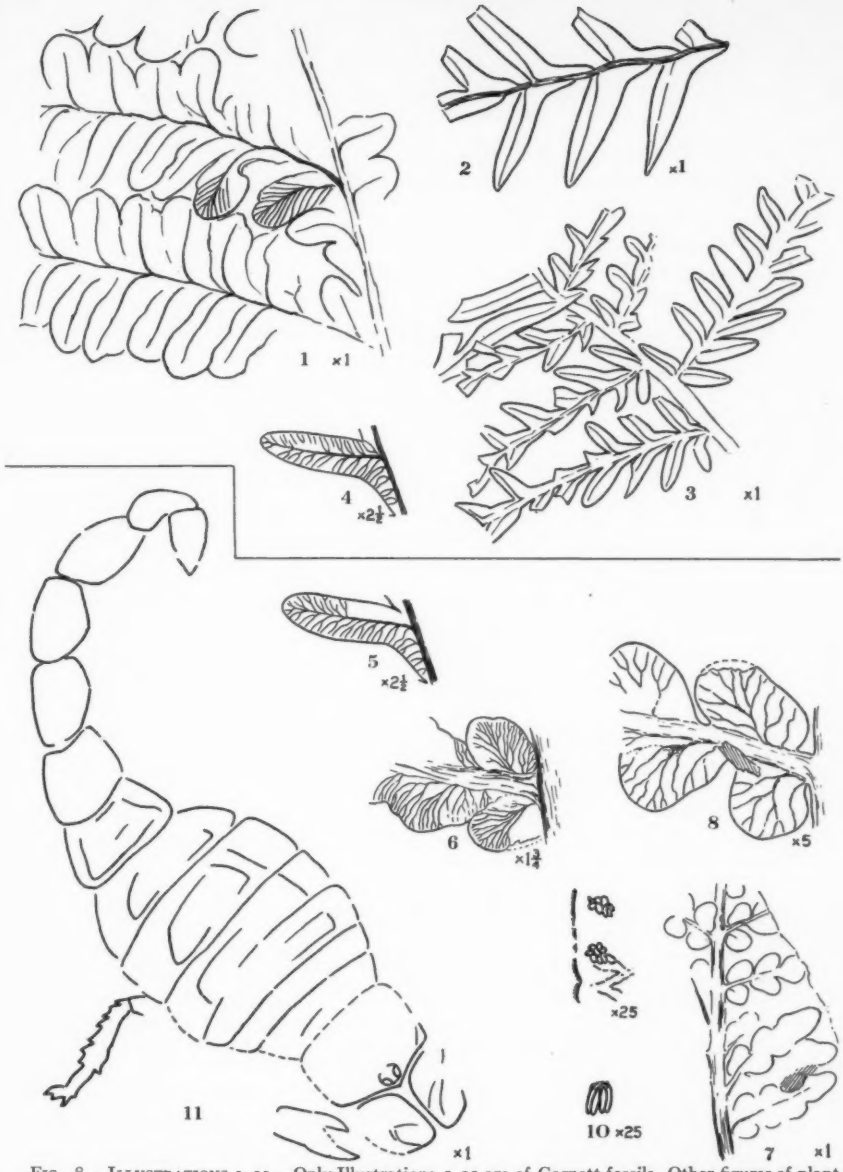

FIG. 8.—ILLUSTRATIONS *1–11*.—Only Illustrations *5–11* are of Garnett fossils. Other figures of plant remains belong elsewhere and are shown for comparison. All illustrations are made from originals unless otherwise indicated. *1*, *Callipteris conferta* (Sternberg); from near base of Wellington shale formation, 5 miles north and 1 mile east of Washington, Kansas; Univ. of Kansas coll. No. 5306; natural size. *2*, *Alethopteris lonchitica* (Schlotheim) [=*A. discrepans* Dawson]; from "Fern Ledges" Carboniferous, St. John, New Brunswick, Canada; adapted from M. C. Stopes; natural size. *3*, *Alethopteris lonchitica* (Schlotheim); from the Mines d'Aniche of Carboniferous of Valenciennes, France; adapted from R. Zeiller; natural size. *4*, *Alethopteris lonchitica* (Schlotheim); from the Pennsylvanian of Washington County, Arkansas; Univ. of Kansas coll.; 2½×. *5*, *Alethopteris kansasensis* Elias, n. sp.; detail sketched from the counterpart of the specimen illustrated in Figure 6, *8;* 2½×. *6*, *Neuropteris whitei* Elias, n. sp.; detail sketched from lower left leaflet of the specimen illustrated in Figure 6, *6;* 1¾×. *7–10*, *Sphenopteris* (*Aneimioides*) *zeilleri* Elias, n. sp.: *7*, sketched from the counterpart of the specimen illustrated in Figure 6, *5;* natural size. *8*, Detail sketched from the specimen shown in Figure 6, *5;* 5×. *9*, Groups of sporangia observable near the margin of a leaflet of the same specimen; 25×. *10*, Restoration of side view of the same groups of sporangia; 25×. *11*, *Mazonia hungerfordi* Elias, n. sp.; sketched from the specimen illustrated in Figure 6, *12*, and from its counterpart; natural size.

is certainly not present. This may now be stated very positively after extensive quarrying of the plant-bearing bed in three neighboring localities during which thousands of plant specimens were uncovered and several scores of fernlike specimens, particularly sought, were collected. All varieties of these remains were shown to Dr. White when I took the collection to Washington in 1933. Although he was very anxious to find *Callipteris conferta* in the flora, he admitted that none of the fossils is suggestive of this species. There is also no indication that any of the remains could possibly belong to other species of *Callipteris*.[7] In view of the abundance of *Callipteris conferta* in every flora of the Big Blue series ("Permian") of Kansas from the Americus limestone horizon upward, the absence of the form in question in the Garnett flora seems to the writer very significant. The significance of the absence of *Callipteris conferta* is further emphasized by the presence of somewhat fragmentary, but nevertheless sufficiently complete and beautifully preserved, remains of *Alethopteris*, which, although not exactly identical with *A. lonchitica* of Europe and North America, belongs undoubtedly to this group, which is characteristically Pennsylvanian in age, and from which "Permian" *Callipteris conferta* has probably been derived.

[7] After this manuscript was completed, I received from Dr. Jongmans of Holland a separate of the paper in which *Callipteris* is claimed to be present (W. J. Jongmans and W. Gothan, *Florenfolge und Vergleichende Stratigrafie des Karbons der östlichen staaten Nord-Amerika's. Vergleicht mit West-Europa*, Geol. Bureau Heerlen, Jaarverslag 1933 [1934], p. 39) in the representative collection from the Garnett locality, which I gave to him in 1933. Subsequent communication with Jongmans has made it clear that the plant which is here illustrated as *Dichophyllum moorei* Elias, n. gen., n. sp., is identified by him as *Callipteris flabellifera* (Weiss) of Europe (letter by Jongmans of May 14, 1935). Basing my opinion on the study of much more complete type specimens in my collections, I disagree with this identification. Specifically, *Dichophyllum moorei* is not identical with *Callipteris flabellifera*. It is true that these two species have some resemblance, but they differ distinctly chiefly by the character of the lateral pinna; in the species from Kansas they are palmate, while in the European form they are pinnate.

It may be appropriately added that *Callipteris flabellifera*, originally described as *Schizopteris*, is a very doubtful *Callipteris*. I believe that this form deserves a new generic name, unless it is congeneric with *Dichophyllum*. It is undoubtedly related to this new genus and to *Mauerites gracilis* Zalessky (*Bull. Acad. Sci. U.S.S.R.* [1933], pp. 289–90, Pl. I). All these forms probably constitute a new family (Dichophylleae) which stands closer to such plants as *Psygmophyllum* and *Baieria* than to *Callipteris conferta* and other typical species of *Callipteris*.

We now come to discussion of the possibility, viewed from biologic standpoints, that the Garnett flora actually belongs to Pennsylvanian time, as is indicated by its geologic occurrence. First, it must be pointed out that the principal genera identified in the Garnett flora are not unknown in beds of undoubted pre-Permian age. *Walchia* has been recognized from the Upper Carboniferous of Western Europe, both on the continent and in the British Isles.[8] Some *Taeniopteris* fronds have been described from the Upper Carboniferous of Europe,[9] while *Dicranophyllum* is usually considered even more typical for the Stephanian than for beds of Permian age.[10] *Ullmania* and *Voltzia* are not known from beds of Pennsylvanian age, but the Garnett specimens that are here provisionally referred to those genera are very fragmentary and, if correctly determined, almost certainly belong to new species. Therefore, they are forms unknown in the Permian.

Considering the individual value of the "Permian" plants as index fossils, it may be said that *Callipteris conferta* is the principal one among the common "Permian" (Autuno-Permian,[11] i.e., Permian defined as beginning with the Autunian) forms which is restricted to the beds of this age. Among all late Paleozoic plants, *C. conferta* was selected by the International Congress on Carboniferous Stratigraphy at Heerlen[12] as a diagnostic species for separation of the Per-

[8] C. E. Weiss, *Fossil Flora der Jüngsten Stein Kohlen formation ek.* (1872), p. 179; R. Kidston, "Flora of the Carboniferous Period," *Proc. Yorkshire Geol. and Polyt. Soc.*, N.S., Vol. XIV (1902), p. 368.

[9] C. Grand 'Eury, *Flora Carbonifère du dépt. de la Loire ...* (1877), p. 171, Pl. VI, Fig. 19; R. Renault and R. Zeiller, *Etudes sur le Terrain houiller de Commentary* (1888), p. 282, Pl. XXII, Fig. 10.

[10] A. C. Seward, *Fossil Plants*, Vol. IV (1919), p. 93.

[11] The diversity of present usage by different authors of the term "Permian" makes desirable some means of indicating a particular definition of "Permian." Since most of the deviations from the original use have been the inclusion of lower and lower stratigraphic elements, it is convenient to designate the different usages by a hyphenated term in which the first word indicates the stratigraphic unit at the base of the Permian as defined. Thus, by "Artinsko-Permian" we may designate the conception of the Permian now held by Russian geologists, while "Autuno-Permian" would indicate the present usage of Permian for western Europe. The redefined "Permian" recently proposed by Grabau and Schuchert may be designated "Uralo-Permian." This is, or should be, a temporary expedient only.

[12] *Comptes rendu*, 1927, p. xxvii.

mian from the Stephanian on paleobotanical grounds, while *Walchia* was no longer considered a diagnostic Permian fossil.[13] In view of this we may conclude that even though the flora at Garnett is perdominantly made up of *Walchia* remains and contains some other forms which are abundant in the "Permian" (Autuno-Permian) of western Europe, the absence of *Callipteris conferta* indicates that the age of this deposit may be older than "Permian." The lowest-known occurrence of *C. conferta* in the Kansas section is at the horizon of the Americus limestone near the base of the Big Blue series, and this series is thought to be of Autunian age. It is of some importance to add that at the horizon of the Wreford limestone, about 300 feet above the Americus limestone, *C. conferta* is abundant. It occurs here associated with *Walchia piniformis* and *Cordaites*, in essentially the same ecologic plant assemblage as at the Garnett locality.

It is interesting and important to note that among the Garnett plant remains there are some forms that seem to indicate Pennsylvanian age for the flora. These include fairly good specimens which, under broad understanding of *Alethopteris lonchitica*, can be identified with this typical Upper Westphalian form of Europe. In agreement with Dr. White, however, I conclude that this form should be considered as a new species, believed by me to belong in the *A. lonchitica* group, which is characteristically Middle Pennsylvanian in age. Another new species of a group that also is most characteristic of the Middle Pennsylvanian is *Neuropteris* (*Mixoneura*) *whitei* Elias, n. sp., comparable to *N. impar* and *N. acuminata*. Still more decidedly Middle Pennsylvanian in aspect is *Sphenopteris* (*Aneimioides*) *zeilleri*, n. sp., which undoubtedly belongs to the *S. obtusiloba* group of Westphalian age and cannot be distinguished from *S. polyphylla* Zeiller (not Lindley and Hutton) described by Zeiller from the "Zone Supérieure" of the Upper Westphalian at Valenciennes,

[13] The Autunian of France, which corresponds to the Lower Rotliegende of Germany and contains *Callipteris conferta*, I believe to be older than the Artinskian of Russia; and if the latter is selected as basal Permian, the Autunian remains in the Carboniferous. Therefore, the paleobotanical definition of the Permian as accepted by the Heerlen Congress of 1927 does not correspond to the limits of the Permian of Russia, but includes a portion of the Upper Uralian correlative to the Autunian and the Lower Rotliegende.

France. The rest of the plants from the Garnett locality are either new or are common to both Pennsylvanian and Lower "Permian" (in the sense that includes the Autunian of Europe and the Dunkard of America).

We may now summarize the evidence in favor of the Middle Pennsylvanian age of the Garnett flora.

The geologic evidence in favor of this age is definite, not to say overwhelming. This aspect has been discussed by R. C. Moore and N. D. Newell. I concur wholly in their conclusions and believe that no one familiar with the geology of Kansas can seriously consider that the plant-bearing beds at Garnett are an outlier of any part of the Big Blue series or the Lower "Permian" of Kansas.[14]

The evidence offered by the marine invertebrates is also definitely in favor of Pennsylvanian age. Most important is the evidence by the fusulinid *Triticites* cf. *T. moorei* (described here by Newell), the bryozoan *Fenestella mimica* var. *A* Elias, n. var.,[15] and by *Chonetes stantonensis* Newell, none of which is known to occur in the Big Blue series of Kansas and Nebraska or in its equivalents in Texas and Oklahoma, being replaced there by closely related but distinctly different species.

According to Carpenter, the megasecopteron wing, *Parabrodia carbonaria* Carpenter, from the Garnett locality is a "wing typical of the European Megasecoptera of this horizon"[16]—the Upper Carboniferous. The fishes related to the new species of *Coelacanthus* described by Hibbard[17] have previously been found in the Mississippian and Lower Pennsylvanian of the northern Mid-Continent area and one species in doubtful Triassic (upper Banff) of Canada. Thus it appears that all evidence, except that seemingly offered by the abundance of *Walchia* and a few other xerophytic plants which were undoubtedly more at home in Permian than in Pennsylvanian time, is either not conclusive or points definitely to Pennsylvanian age. After reaching this conclusion, it remains to explain why a

[14] The late Dr. D. White was convinced of this, I believe, after the detailed geologic map and sections of eastern Kansas had been shown to him.

[15] This form is described, together with other Bryozoa of the Garnett locality, in a forthcoming paper in the *Journal of Paleontology*.

[16] Carpenter, *op. cit.*, p. 365.

[17] *Op. cit.*, p. 279.

xerophytic assemblage of "Permian" aspect occurs in Kansas in beds of Middle Pennsylvanian age.

Ecologic aspects of the Garnett flora.—Is it not possible reasonably to explain the predominance of conifers and other gymnosperms at Garnett on the basis of purely ecological considerations? First, no matter what opinion we accept as to the age of this flora, it appears that these plant remains represent a xerophytic association. This does not necessarily mean a desert flora or a flora requiring the semi-arid continental conditions of today; but in view of the predominance in late Paleozoic time of pteridophytes, which are mostly hydrophytes, the plant group at Garnett can certainly be considered as an association adapted to a dry-soil environment. Most of these plants were propagated by seeds. *Walchia* and other conifer-like plants of the locality, *Dicranophyllum* and *Cordaites*, are classed with the gymnosperms; and the fernlike remains of Garnett belong in part to extinct genera which are now classed with more or less certainty as Pteridospermeae, or fernlike plants which bore seeds. Another fact in favor of this view is the occurrence in the Garnett flora of a leaflet of *Neuropteris* in direct connection with a seedlike fruit. The true ferns of the flora, *Sphenopteris* (*Aneimioides*) *zeilleri* Elias, n. sp., and *Alethopteris kansasensis* Elias, n. sp., on which I recognized the presence of sporangia disposed at the edges of leaflets, have distinctly reduced foliage which indicates xerophytic adaptation. The reduction of foliage in comparison with increased stoutness of the rachis is also quite evident in *Neuropteris whitei*. *Annularia* is the only plant of the Garnett association which is usually considered as a representative of the Equisetaceae, but the very small *Annularia* of Garnett is certainly a dwarfed representative of a plant that is ordinarily much larger. Furthermore, as I have recently demonstrated,[18] some annularias bore seedlike fruits.

All in all, it is evident that the Garnett plant association was fit to grow on dry land, or at least on well-drained land, that was uncongenial to pteridophytes, which need moist ground conditions for fertilization (their sperm cells being free-swimming) and for development of the prothallus. The Garnett plants are mostly gymnosperms, and we know that ecologically the living gymnosperms are

[18] M. K. Elias, *Univ. Kansas Sci. Bull. 20* (1931), p. 115.

all terrestrial plants, living in somewhat drier places on the whole than the angiosperms, and, certainly, in much drier situations than the living pteridophytes and their kin.

A logical conclusion generally held by botanists is:

> Our existing gymnosperms are a survival of those which, the first to develop the pollen tube, were able to occupy drier situations upon the earth than were possible to the true pteridophytes, with their need for keeping a prothallus upon wet ground. Thus we can imagine a time when the forests of the earth consisted of pteridophytes in the moist places with gymnosperms in those which were drier, though both groups have since been largely displaced in both situations by the angiosperms.[19]

The existence of many gymnosperms, including conifer-like plants of the *Walchia* type, in Pennsylvanian time has already been established, and now the Garnett flora seems to show that these early conifers and associated seed-bearing plants formed a distinct plant group that lived during Pennsylvanian time in a different environment from that of the ferns, calamites, and lepidophytes. They do not occur merely as an admixture in the predominant Pennsylvanian forests of pteridophytes. This agrees with the assumption stated by David White in one of his latest papers, that *Walchia*, as well as other late Paleozoic conifers, "appears to have had its origin in the effort of a moist-climate flora to withstand increasingly dry summers," and "becomes relatively prominent as proof of aridity is more abundant."[20] We know, furthermore, that conifer forests were not the only kind of vegetation of Permian time. There certainly existed plant associations composed chiefly of ferns and other mesophytes which, though possibly not so common as the conifer forests, nevertheless grew here and there in the more moist portions of the Permian land.

The same seems to be true for the Pennsylvanian flora, except that the ferns, horsetails, lycopods, and other hydrophytic forms were by far the most abundant in Pennsylvanian time. The xerophytic floras were rare or, more likely, occupied areas such as the higher lands, in which there was less chance for preservation of their remains in the sediments now available for study. It appears that

[19] W. F. Ganong, *Textbook of Botany* (New York: Macmillan Co., 1923), p. 517.

[20] D. White, "Flora of the Hermit Shale," *Carnegie Inst. Wash., Publ. 405* (1929), p. 24.

the Garnett flora represents this either rare or rarely preserved dry-soil or high-land flora of Pennsylvanian time.

Cyclic climatic changes of late Paleozoic time in Kansas.—There remains to be explained why this xerophytic flora, which probably occupied higher land normally, appears in profusion in the upper portions of the Stanton limestone formation of Kansas. An analysis of the distribution of other floras of the Mid-Continent region seems to indicate that this appearance of a *Walchia* flora at the end of the Missouri time was not entirely accidental. Most other known floras of the Missouri group also have a decidedly xerophytic aspect, although neither *Walchia* nor any other conifer-like gymnosperms have been found in them as yet. The most common floras of the Missouri group are composed predominantly of *Cordaites*, with which only a few fragmentary remains of ferns or pteridosperms are usually mingled. These ferns are distinctly different from the common Pennsylvanian forms collected in mesophytic fern-sphenophyll associations, either in rocks of the Missouri series or in older or younger beds. Compared with the known floras of the upper Des Moines, which consist chiefly of ferns, pteridosperms, sphenophylls, lycopods, cordaites, etc., the floras of the Missouri series seem to indicate a general change to drier climatic conditions, which culminated toward the end of Missouri time (occurrence of *Walchia* flora). The occurrence of the xerophytic assemblages in Missouri time does not indicate that they did not exist previously, but it does suggest that these floras which occupied higher and more secluded spots in Des Moines time, descended in Missouri time to lower areas that had become drier, and thus they came closer to the sea where their remains might be buried in the near-shore sediments. With the return of more moist climatic conditions in Virgil time, these floras moved back to the higher portions of the land, while the mesophytic and hydrophytic vegetation established itself again in the broad lowland zone. Thus in the Stranger and Lawrence formations in the basal part of the Virgil series, the prolific floras which succeed the *Walchia* flora of Garnett are chiefly made of ferns, pteridosperms, sphenophylls, calamites, and lycopods which are only rarely accompanied by *Cordaites*. Drier climatic conditions came again in late Virgil time, after which general mesophytic conditions returned once

more in Big Blue time. The place of the Garnett xerophytic flora among the other known floras in the geologic column of Kansas and adjacent area is shown in Figure 3. The cyclic character of the climatic changes indicated by the changes in the character of the floras is also shown on this chart.

It is of interest to add that *Walchia* has recently been reported from the upper Conemaugh beds of Pennsylvania.[21] This occurrence, according to the writer's correlation based on other floral evidence, corresponds approximately to the occurrence of *Walchia* in the Garnett flora. The entire character of the Conemaugh division with its scarcity of coals and abundance of red beds seems to indicate somewhat drier climatic conditions, which agrees with the recognized climatic changes in the Mid-Continent region during Missouri time. Thus, a general tendency toward greater dryness appears to have affected at least the eastern half of the territory now occupied by the United States in mid-Pennsylvanian time.

STRATIGRAPHY OF THE GARNETT FOSSIL LOCALITY

NORMAN D. NEWELL

It is the aim of this discussion to present evidence that the *Walchia* assemblage occurs within the Stanton formation of the Lansing group. The Lansing beds occur near the middle of the Pennsylvanian system as it is developed in Kansas. The main thesis is that the beds containing the *Walchia* biota underlie a widely distributed thin limestone which in northeastern Kansas and northwestern Missouri is the uppermost member of the Stanton formation.

Section at the Garnett locality.—The general location of the fossil quarry in Anderson County is shown in Figure 9. The quarry from which the bulk of the conifer flora has been obtained occurs in the southwest part of the southeast quarter of Section 32, T. 19 S., R. 19 E., about 6 miles northwest of Garnett, county seat of Anderson County, Kansas. Figure 10 includes a detailed sketch map and section of a small area around the quarry, showing the distribution and

[21] C. Darrah and Paul Bertrand, "Observations sur les flores houillères de Pennsylvanie," *Ann. Soc. Géol. du Nord*, Vol. LVIII (1933), p. 221; also D. White, "Some Features of the Early Permian Flora of America," *Rept. XVI Intl. Geol. Cong.* (Washington 1933), p. 9 and chart opposite p. 10.

relation of rock units. A profile drawn along the line *AB* intersects the quarry and passes along good road-cut exposures.

The formations cropping out in the vicinity of the Garnett fossil locality are classified in Table I.

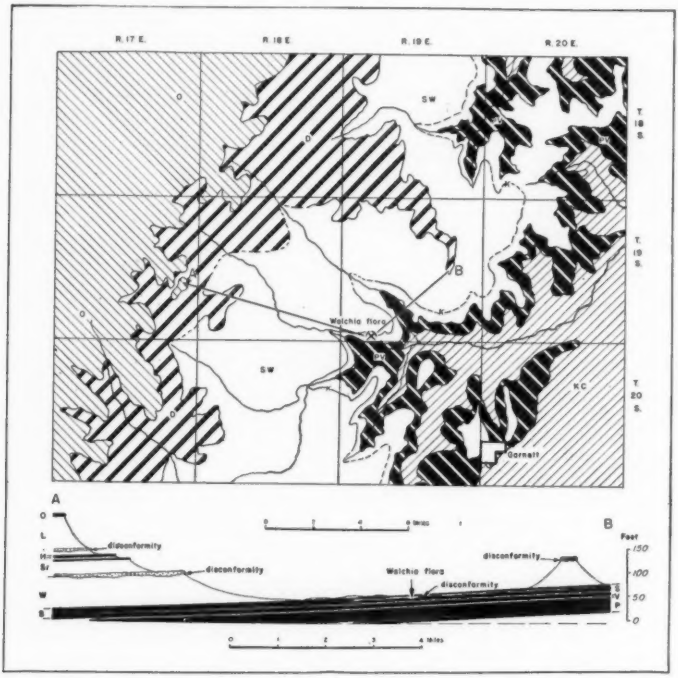

FIG. 9.—*Upper:* Areal geologic map showing location of profile *AB*. *O*, Oread limestone and higher; *D*, Douglas group, including Lawrence, Haskell, and Stranger formations; *SW*, Weston and Stanton formations, including Little Kaw limestone, *K; PV*, Vilas and Plattsburg formations; *KC*, Kansas City group. *Lower:* East-west profile showing regional relations of the *Walchia* beds to older and younger formations. *O*, Oread limestone; *L*, Lawrence shale; *H*, Haskell limestone; *Sr*, Stranger formation; *W*, Weston shale; *S*, Stanton limestone; *V*, Vilas shale; *P*, Plattsburg limestone.

The Stanton limestone formation has been subdivided into the following members:

Little Kaw limestone
Victory Junction shale

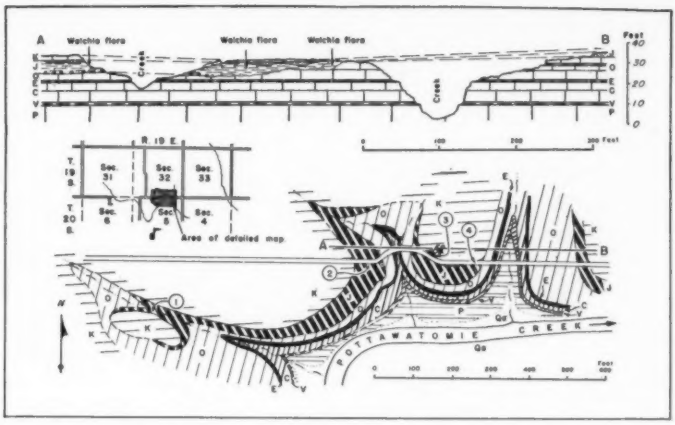

FIG. 10.—*Upper:* East-west profile along road at the Walchia locality; symbols are same as on map. *Lower:* Map of the locality of the Garnett flora. *Qa*, alluvium; *K*, Little Kaw limestone; *J*, Victory Junction shale; *O*, Olathe limestone; *E*, Eudora shale; *C*, Captain Creek limestone; *V*, Vilas shale; *P*, Plattsburg limestone. Numbered localities have yielded the *Walchia* flora.

TABLE I

Series	Group	Formation	Thickness (Feet)
Virgil	Shawnee	Oread limestone	35+
	Douglas	Lawrence shale	80
		Haskell limestone	2
		Stranger formation	60±
Unconformity			
Missouri	Pedee	Weston shale	60±
	Lansing	Stanton limestone	32
		Vilas shale	2
		Plattsburg limestone	35
	Kansas City	Bonner Springs shale	15
		Wyandotte limestone	1±
		Lane shale	70

Olathe limestone
Eudora shale
Captain Creek limestone

The soft argillaceous shale of the Weston formation, cropping out in a relatively broad band across the western part of Anderson and Franklin counties, has been cut down by erosion to a broad upland plain established at or near the top of the resistant beds of the Stanton limestone. The Garnett fossil locality is situated on this upland plain.

The fossil quarry is located at the summit of the north bluff of Pottawatomie Creek. About 40 feet of strata are exposed in the near

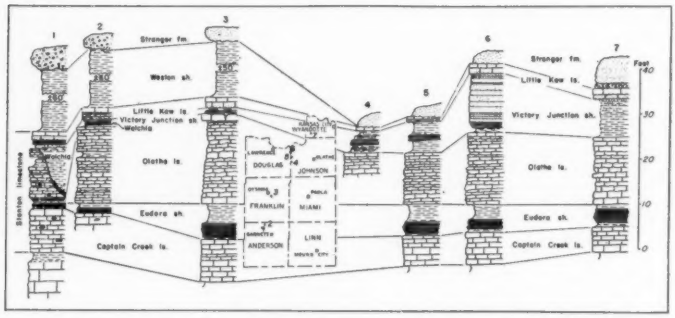

FIG. 11.—Correlation of members of the Stanton formation (Captain Creek, Eudora, Olathe, Victory Junction, and Little Kaw) and their relation to the unconformity at the base of the Stranger formation in northeastern Kansas.

vicinity, including beds below and above the horizon of the fossil plants.

Correlation of the upper limestone.—The uppermost limestone exposed in the vicinity of the *Walchia* quarry rests immediately on the shaly beds bearing the plant assemblage. Because this fact cannot be questioned, it is very important to establish the regional correlations of the limestone.

The sections shown in Figure 11 represent the principal localities between the Kansas River sections and the locality of the Garnett flora where the relations of the top member of the Stanton can be clearly seen. In order to indicate the relation of the basal unconformity of the Virgil series to the Stanton formation, composite sec-

tions of the Weston and Stranger formations are added to the Stanton sections.

The Captain Creek limestone, lowermost member of the Stanton formation, consists in the region between Kansas River (Fig. 11, secs. 4–7) and the *Walchia* quarry (sec. 1) of 6–10 feet of fine-grained, bluish-gray, even-bedded limestone containing a very characteristic fauna.

The Eudora member on Kansas River comprises about 6 feet of shale, the middle and lower parts being chiefly black and fissile. Southward the member thickens locally around Ottawa (sec. 3) but thins to about a foot at the *Walchia* locality (sec. 1).

The Olathe limestone likewise is fairly uniform and characteristic. It is composed of thin irregular beds of white or light-gray limestone and generally measures around 20 feet, except in the vicinity of the *Walchia* quarry, where it has been reduced by pre-Victory Junction erosion.

Along Kansas River (secs. 6 and 7) the Victory Junction member contains up to 12 feet of brown, evenly bedded, friable sandstone with marine fossils. This sandstone is commonly underlain abruptly by a little more than a foot of greenish clay. Proceeding southward along the stream called Captain Creek (secs. 4 and 5), the sandstone thins abruptly and a whitish, very even, and thin-bedded shaly limestone appears below it. The nearest good outcrop of the Victory Junction member to the southwest of the outcrops along Captain Creek is seen at a quarry of the Central Kansas Quarries Company southeast of Ottawa (sec. 3). At this place the member is represented by about $1\frac{1}{2}$ feet of sandstone and sandy shale, probably equivalent to part of the sandstone along Kansas River. The next good outcrops of the member are graphically illustrated in sections 2 and 1. The lower and middle parts of the member contain whitish calcareous shale with intercalated shaly limestone that cleaves like shale. These strata contain the *Walchia* flora and other unusual biota. The upper part of the member, as at the outcrops farther northeast, consists of brown marine sandstone with a molluscan fauna. The sandstone is highly lenticular and appears to be locally absent. It is quite thin but nevertheless present in the region of the Garnett flora.

The Little Kaw limestone is sufficiently distinctive to be definitely recognized at a large number of isolated outcrops. At Kansas River in the vicinity of Eudora, and along Captain Creek, it consists of 1 to 2 feet or more of bluish-gray, even limestone which weathers brown (secs. 5 and 6). The upper part is commonly dense and the lower part arenaceous. These characters are maintained across Johnson and Franklin counties, with an increase in thickness locally to 4 feet or so in southern Franklin and northern Anderson County. The increase in thickness occurs chiefly in the lower arenaceous part of the member and this part is locally cross-bedded and conglomeratic in Anderson county, containing a molluscan fauna. The thin limestone overlying the *Walchia* flora near Garnett agrees in lithologic character and position with the upper member of the Stanton formation as elsewhere exposed.

Fossil invertebrates.—The lower three-fourths or more of the Victory Junction member has yielded fossils only in the vicinity of the *Walchia* quarry. The following invertebrates were found on bedding planes with the *Walchia* flora and vertebrates: *Composita* sp., *Neospirifer* sp., *Myalina* cf. *meeki* Dunbar, *Lingula carbonaria* Shumard, *Yoldia* sp.?, *Sedgwickia topekaensis* (Shumard), *Rhombopora lepidodendroides* Meek, *Fenestella mimica* var. A, Elias, n. var., *Fenestella geminanoda* Moore, *Fenestella pectinis* Moore, *Polypora elliptica* Rogers, *Rhombopora lepidodendroides* Meek, *Parabrodia carbonaria* Carpenter, and *Mazonia hungerfordi* Elias, n. sp. The bryozoans were identified by M. K. Elias. The species of *Lingula*, *Sedgwickia*, and *Myalina* are relatively abundant and suggest a brackish water or otherwise abnormal environment.

The fossiliferous sandstone at the top of the Victory Junction bears a molluscan fauna, of which pelecypods are the most abundant as regards individuals. The following species are particularly common at this horizon: *Derbya crassa* Meek and Hayden, *Derbya crassa* var. *richmonda* (McChesney), *Aviculopecten occidentalis* (Shumard), *Monopteria marian* White, *Edmondia subtruncata* Meek, *Myalina kansasensis* Shumard, *Myalina subquadrata* Shumard, *Myalina* cf. *wyomingensis* (Lea), *Myalina? swallowi* McChesney, *Pseudomonotis* cf. *hawni* (Meek and Hayden). Practically all of these forms were found at the top of the Victory Junction shale at

stations 1, 2, and 6 (Fig. 11), and at a number of places north of Kansas River. This assemblage does not occur, however, in the lower three members of the Stanton. At station 3 (Fig. 11), a number of specimens of *Chonetes granulifer* var. *stantonensis* Newell[22] were found with some less significant fossils at the top of the Victory Junction shale. This subquadrate variety of *Chonetes granulifer* apparently is not represented above the Stanton horizon in the extensive collections at Peabody Museum, Yale University, nor have I seen it above the Missouri series in my field work. Certainly there is nothing comparable with it in the Kansas "Permian." On the other hand, the variety is common in the Little Kaw member of the Stanton. The typical *Chonetes granulifer* Owen from the Douglas group is a somewhat more alate form and is characteristically larger.

Other characteristic elements of the Little Kaw fauna throughout northeastern Kansas are abundant *Meekella* cf. *striatocostata* Cox and a small *Triticites* cf. *moorei* Dunbar and Condra. The fauna of the upper limestone at the *Walchia* quarry is in full accord with the typical Little Kaw fauna. A dozen or so more or less imperfect specimens of the *Triticites* were collected from the Little Kaw limestone immediately above the *Walchia*-bearing shales. The limestone definitely overlies the shales with clearly defined stratigraphic relations. All of the fusulinids occur in dense to fine-grained bluish-gray limestone within a narrow zone at the top of the member.

There are four described forms with which the present one may be compared; it differs, however, from all of them. In general expression the species at hand is similar to *Triticites moorei* from Texas.[23] It resembles *moorei* in form, size, number of volutions, size of proloculum and size of tunnel angle; furthermore, the tunnel angle expands regularly in the outer volutions. The external sulci are relatively deep, as in *moorei;* and free specimens from the Little Kaw at Ottawa, Kansas, show the peculiar eccentric growth characteristic of *T. moorei*. Our species is distinct from typical *moorei* in being almost

[22] Norman D. Newell, *Jour. Paleontol.*, Vol. VIII, No. 4 (1934), pp. 430–31, Pl. 55, Figs. *2a–j*.

[23] C. O. Dunbar and G. E. Condra, *Neb. Geol. Surv., Bull. 2*, Ser. 2 (1927), p. 99, Pl. 1, Fig. 3; Pl. 9, Fig. 4; Pl. 11, Figs. 1–5; Graham formation, South Bend shale member, Texas.

devoid of septal pores and in having a definitely lower rate of expansion of successive volutions, and furthermore it is somewhat more intensely fluted than in typical *moorei*. *T. cullomensis* Dunbar and Condra and *T. secalicus* (Say) are larger forms with a larger tunnel angle and less intensely fluted septa.

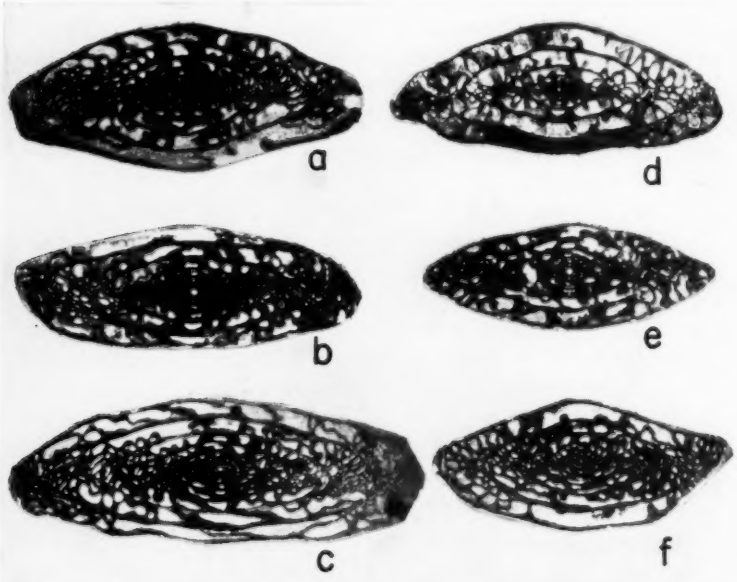

FIG. 12.—Fusulinids from the Little Kaw limestone. *a, b, c, f, Triticites* cf. *moorei* Dunbar and Condra; from a thin limestone overlying the *Walchia* flora near Garnett, Kansas. *d, Triticites moorei* Dunbar and Condra; a characteristic topotype specimen from the South Bend shale of mid-Pennsylvanian age at Graham, Texas. *e, Triticites* cf. *moorei* Dunbar and Condra; a small acute specimen from the Little Kaw limestone at a quarry of the Central Kansas Quarries Company, 1 mile southeast of Ottawa, Kansas. ×10.

The form described by Maynard White under the name *T. acutus*[24] is comparable to the present one but is somewhat longer and its successive volutions are notably higher.

There are no fusulinids from the Big Blue series and equivalent

[24] *Texas Univ. Bull. 3211* (1932), p. 32, Pl. 2, Figs. 1–6; Caddo Creek formation, Texas.

horizons that could be compared with our species from the *Walchia* locality.

A characteristic individual of *Linoproductus platyumbonus* Dunbar and Condra was found in the Little Kaw limestone just above the *Walchia* shale. This productid has never been found above the Stanton limestone in the northern Mid-Continent, although the species is relatively common in that formation.

The lower part of the Little Kaw limestone near the *Walchia* quarry bears a molluscan fauna exactly like that of the thin sandstone just underneath it. The full invertebrate fauna collected from the Little Kaw limestone at this place, definitely above the *Walchia* beds, is as follows: *Chonetes granulifer* var. *stantonensis* Newell, *Triticites* cf. *moorei* Dunbar and Condra, *Linoproductus platyumbonus* Dunbar and Condra, *Meekella* cf. *striatocostata* Cox, *Neospirifer* sp.?, *Composita subtilita* (Hall), corals, indet., echinoid plates, *Myalina kansasensis* Shumard?, *Aviculopecten occidentalis* (Shumard), *Edmondia subtruncata* Meek, *Pseudomontis* sp.?, *Schizodus curtus* M. and W., *Pteria longa* (Geinitz), *Pleurophorus* sp., *Monopteria marian* White, *Bellerophon* sp., *Fenestella limbata* Foerste, *Fenestella pectinis* var. C Elias, n. var., *Polypora nodocarinata* Ulrich, *Polypora elliptica* Rogers, *Polypora* sp. D Elias, n. sp., *Rhombopora lepidodendroides* Meek. The bryozoans were identified by Elias.

From the foregoing discussion it will be seen that the *Walchia* beds near Garnett, Kansas, may be identified definitely as the Victory Junction member of the mid-Pennsylvanian Stanton formation. Although the aspect of the fossil flora will suggest a much higher horizon ("Permian") to some students, the evidence of lithologic and faunal continuity of the upper limestone of the Stanton which immediately overlies the *Walchia* beds permits no doubt that they lie within the Stanton formation.

GRANITIC INJECTION PROCESSES IN THE COLUMBIA QUADRANGLE, SOUTH CAROLINA[1]

THOMAS L. KESLER
United States Geological Survey

ABSTRACT

Studies in the Columbia quadrangle lead to the following conclusions: (1) intrusion of granite and conversion of volcanic and sedimentary rocks into schist are results of the same geologic cycle; (2) schist near the granite has been subjected to lit-par-lit injection and replacement by granitic material; (3) an advanced stage of injection and replacement is expressed by granitic rock in which schistose and gneissic structures are preserved. In the extreme stage, replacement and recrystallization have obliterated most of the inherited structure, the resulting rock being a granite contaminated by traces of the older rocks, with consequent marked variations in composition and structure; (4) no granite was found that had undergone mashing or other appreciable deformation except ordinary fissuring.

INTRODUCTION

The field work on which this paper is based was done during the summer of 1934 incidental to a survey of the gold deposits of the southern states. This program was carried on through funds allocated to the United States Geological Survey by the Public Works Administration, and was under the general direction of J. T. Pardee. The writer was assigned to South Carolina, and was instructed to give special attention to granite as well as gold deposits. Slightly more than four months were spent in the field, and less than half of this could be devoted to granite, but the results obtained seem worthy of presentation as a contribution to our knowledge of intrusive processes. Reports by Sloan[2] and Watson[3] have described the quarries of the state in detail, and the writer concentrated his efforts on an interpretation of general intrusive features. For this purpose, the Columbia 30-minute quadrangle was chosen, which includes the most active quarries in the state. As only three weeks

[1] Published by permission of the Director, U.S. Geological Survey.

[2] Earle Sloan, "Mineral Localities of South Carolina," *S.C. Geol. Surv. Bull. 2* (1908), 4th ser.

[3] T. L. Watson, "Granites of the Southeastern Atlantic States," *U.S. Geol. Surv. Bull. 426* (1910).

could be devoted to the study of this quadrangle, only reconnaissance mapping was possible; nevertheless, certain features were so consistent and persistent as to provide a general understanding of relationships. Study of the gold deposits, which carried the writer entirely across the eastern piedmont portion of South Carolina, revealed that these features are uniform and widespread, and observations were frequently made that supplemented and verified those made in the Columbia quadrangle.

The writer wishes to express his appreciation for much assistance and criticism from many members of the Geological Survey. Particular help in petrographic study and general discussion was rendered by Arthur Keith, A. H. Koschmann, C. P. Ross, C. S. Ross, and L. W. Currier. Special thanks are expressed to G. F. Loughlin for consultation in the field and during the preparation of this paper.

TOPOGRAPHY

The Columbia 30-minute quadrangle lies in the eastern portion of the Piedmont Province in South Carolina, and comprises approximately 1,045 square miles. The topographic map of the quadrangle, surveyed in 1901–2 on a scale of 1:125,000, has proved a satisfactory base map for the general study thus far made, although a map of much larger scale will be essential for the detailed work that should follow. The entire quadrangle is characteristic of the southern Piedmont in its late mature topography. It is drained by the Broad and Saluda rivers, which unite at the city of Columbia to form the Congaree. The rivers and their larger tributaries occupy valleys that are commonly broad and flat-bottomed, and are separated by moderately sloping divides that represent the Tertiary peneplain. Altitudes range chiefly between 200 and 550 feet. The damming of the Saluda River has developed Lake Murray, a large reservoir which covers much of the southern part of the quadrangle.

In uplands and valleys alike, extreme development of saprolites is a factor that seriously affects field work. It is common to find granite and older rocks thoroughly weathered to depths of 25 and 50 feet, and several mine shafts in the state disclose fresh rock only at depths of 75 or 100 feet. Such a general condition necessitates close observation of the saprolites, which are found particularly well ex-

posed in the newer road cuts and gullied hillsides, where they preserve many of the details of composition and structure revealed by fresh exposures.

THE PRE-GRANITE ROCKS

The pre-granite rocks of the quadrangle constitute a wide series which is believed to extend at least from Virginia to Alabama. The writer has found the belt to extend southwestward completely across South Carolina. As far back as the days of Olmsted,[4] the North Carolina portion of the belt was called "the great Slate Formation." In later years, despite several efforts at correlation, it has been loosely known as the "Carolina slate belt" or simply the "slate belt." In South Carolina no persistent horizons have been recognized in it that can form a basis for division into formations. Keith and Sterrett have called a metamorphosed facies that extends southwestward across the Kings Mountain quadrangle the Battleground schist,[5] but no other local names have been proposed for any part of it. In the early days it was recognized to consist chiefly of volcanic rocks. It has subsequently been studied in detail in a few localities, notably by Laney[6] and Pogue[7] in North Carolina and by Keith and Sterrett[8] in northern South Carolina, and has been given more casual attention by many workers. Where it has been studied in detail the "slate belt" has proved to consist largely of water-laid rhyolitic and andesitic tuffs and breccias, with varying admixtures of fine-grained land waste, the whole interlayered with rhyolitic and andesitic flows and cut by sills and a few dikes of rhyolitic, andesitic, and gabbroic composition. The sills may have been intruded at many different times, but all those noted by the writer in South Carolina are distinctly older than the granite.

[4] Denison Olmsted, "Geology of North Carolina," *N.C. Board of Agric. Rept.*, Part I (1824), p. 23.

[5] Arthur Keith and D. B. Sterrett, "Gaffney–Kings Mountain Folio," *U.S. Geol. Surv. Folio 222* (1934), p. 4; also oral information by Keith in 1934.

[6] F. B. Laney, "The Gold Hill Mining District of North Carolina," *N.C. Geol. and Econ. Surv. Bull. 21* (1910).

[7] J. E. Pogue, Jr., "Cid Mining District of Davidson County, North Carolina," *N.C. Geol. and Econ. Surv. Bull. 22* (1910).

[8] *Op. cit.*

Most of the "slate belt" in and around the Columbia quadrangle has undergone recrystallization to some degree, and has therefore lost some of its original mineral composition and texture. The writer, however, is familiar with the belt in North Carolina, where its original features are well preserved, and has recognized many of these features in a number of places in the Columbia quadrangle, particularly east and north of Lake Murray and east of Whiteoak. The rocks east and north of Lake Murray, which are the least metamorphosed of any in the quadrangle, consist of parallel layers of salic tuffaceous rock intermingled with partly or entirely argillaceous members. Mafic members are not conspicuous in this region, partly because of their scarcity, and partly because of their greater tendency to weathering and consequent concealment. East of Whiteoak, where the rocks of the "slate belt" are somewhat nearer to a large, exposed granite mass, original bedding is well preserved in spite of the fact that the microscopic clastic texture of the argillaceous and the salic tuffaceous beds has been largely or wholly destroyed by recrystallization. The proportion of mafic members is much greater than in the area about Lake Murray. These mafic members are recrystallized to such a degree that their original clastic, extrusive, or intrusive origin has not been distinguished by the writer in the brief time available.

The normal strike of the older rocks in the Columbia quadrangle ranges from N.55° to 75° E., and dips are steeply northwest, except for local and irregular steep reversals for which no general explanation can yet be offered. These reversals are found most commonly in areas adjacent to the granite, where injection and replacement by the magma may have weakened the rocks sufficiently for them to yield to stresses exerted by the intrusion. In areas where these rocks dip at small angles, minor folds are rather common, and broad, regional folds are mostly very gentle. Where dips are steep, as in the Columbia quadrangle, the possibility of close folding is recognized, though the writer has been unable to find any positive indication of it. No addition can be made to previous knowledge regarding thickness and major structural relations of the "slate belt" other than to emphasize the generally uniform steep dip in the Columbia quadrangle, and the fact that it was developed distinctly earlier than the

intrusion of the granite. However, the "slate belt" throughout South Carolina has so consistent a development of metamorphic features, generally accompanied by steep dips, in areas that have been clearly affected by granitic intrusion, that a direct relationship between disturbance, metamorphism, and granitic intrusion is strongly suggested. The evidence harmonizes with Keith's general conclusions that deformation and metamorphism of rocks in the Appalachian region were caused by batholithic intrusions.[9]

Fortunately the belt yields weathered material of very characteristic appearance, a fact that aids greatly in tracing it through saprolitic areas. The more felsic portions of the least altered rock weather to khaki, tan, buff, and yellow, and the schists derived from them weather to white, gray, and tan material frequently spotted or uniformly stained brown, yellow, red, and purple by the oxidation of pyrite. The more mafic zones of the belt weather to a darker khaki, olive, green, and brown, regardless of metamorphism.

THE GRANITE

From quarries located in the granite masses in the quadrangle, Sloan[10] reports a uniform composition which he also records rather consistently for the other masses throughout the piedmont section of the state. Microcline and oligoclase are dominant, with microcline usually in greatest abundance. With them occur quartz, biotite, and micropegmatite. Accessory minerals are apatite, magnetite, chlorite, zircon, and occasional muscovite associated with the biotite. This composition is general for the pure or even slightly contaminated granite, and is checked by Watson,[11] who differs only in reporting the additional presence of microperthitic intergrowths of orthoclase and plagioclase. The process causing contamination, to be described presently, has resulted in marked variations in composition, particularly near the borders of the granite masses. Litpar-lit injection, replacement, stoping, and the intrusion of ramifying granite apophyses into the wall rocks have combined to obscure

[9] "Outlines of Appalachian Structure," *Geol. Soc. Amer. Bull. 34* (1923), pp. 313–14, 321, 365, 368, 372–73; "Major Structures and Intrusions in New England," *Jour. Wash. Acad. Sci.*, Vol. XXI, No. 10 (1933), abst., pp. 486–87.

[10] *Op. cit.*

[11] *Op. cit.*

the exact boundaries of the main granite masses. The complex marginal zone produced by these processes is very narrow in some places, but for the most part it extends for hundreds or even thousands of feet into the wall rocks. Near the marginal zone, huge masses of rock cut by dikes, sheets, and stringers of granitic material are isolated within the granite, which nearby is also full of smaller fragments that not only contain stringers of granitic material mechanically injected along their bedding planes, but also have become impregnated or replaced to different degrees. These fragments, which range from a few inches up to many feet in diameter, may be seen in quarry faces and occasionally in weathered outcrops. In some fragments injection took place before stoping, for the granite stringers end abruptly against the enclosing granite; in others, however, the stringers blend with the surrounding granite or with pegmatitic stringers in the granite, and indicate injection after stoping; in still others there is no distinction in time between stoping and injection, and the two evidently took place concomitantly. The network of granite dikes in some portions of the wall further emphasizes the importance of mechanical means of intrusion, and shows that the granite was in process of extending its limits when solidification near the contact was completed.

Figure 1 shows the distribution of exposed granite bodies in the Columbia quadrangle, as well as the structural trends of the "slate belt." Both the granite and the older rocks are overlain in the southeast part of the quadrangle by the Tuscaloosa formation. The distribution of these granite bodies, together with the distribution of similar bodies throughout the eastern Piedmont portion of the state, indicates a possible continuous subjacent source. An essentially uniform magma is indicated by thin sections and chemical analyses of most of these widespread bodies. Furthermore, the many exposed masses are separated by portions of the "slate belt" which show some degree of metamorphism practically everywhere, even though several miles distant from exposed granite. Harker and Marr,[12] in a study of the intrusive effects of the Shap granite on volcanic rocks in Westmorland, England, found that metamorphism extended only

[12] A. Harker and J. E. Marr, "The Shap Granite and the Associated Igneous and Metamorphic Rocks," *Quar. Jour. Geol. Soc. London*, Vol. XLVII (1891), p. 267.

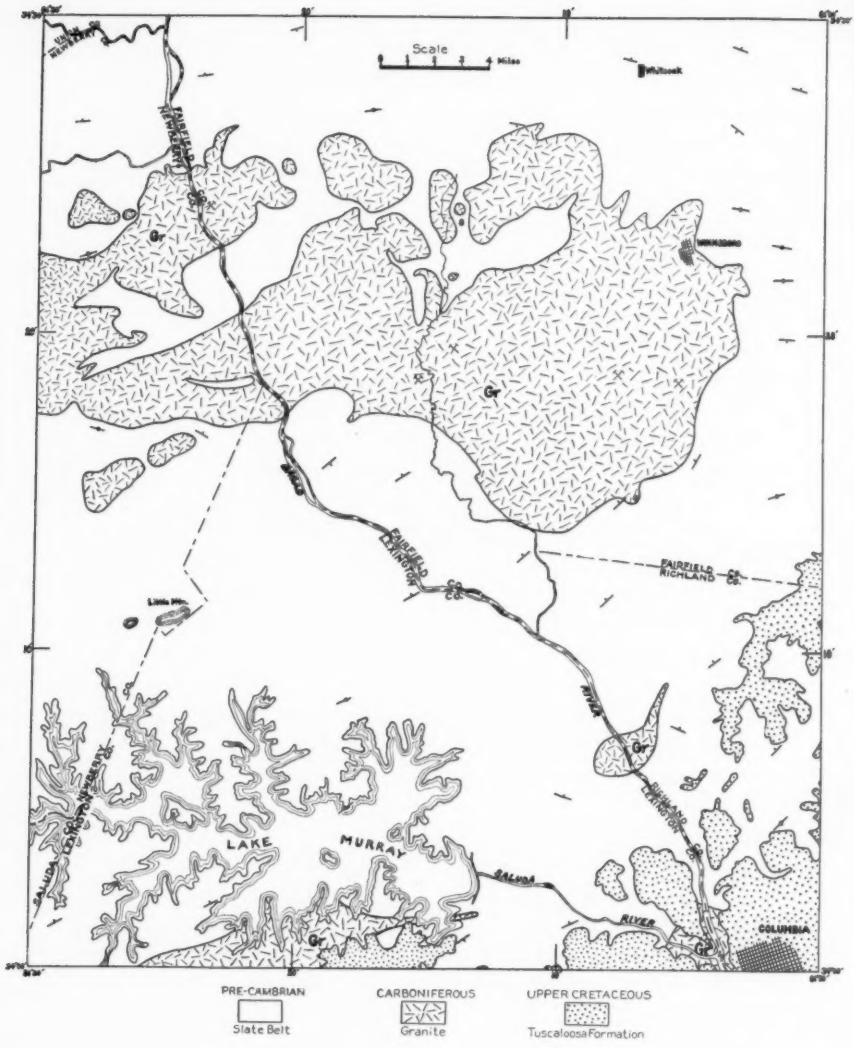
Scale
0 1 2 3 4 Miles
Whitmire
FAIRFIELD NEWBERRY
Gr
FAIRFIELD LEXINGTON
FAIRFIELD RICHLAND
Lone Pine
RIVER
Gr
RICHLAND LEXINGTON
LAKE
MURRAY
SALUDA
RIVER
COLUMBIA
PRE-CAMBRIAN
Slate Belt
CARBONIFEROUS
Granite
UPPER CRETACEOUS
Tuscaloosa Formation

FIG. 1

about 1 mile from the border of the granite. As the narrower metamorphic zones in South Carolina suggest a similar range of influence of intrusive masses now exposed, the wider areas of metamorphosed rocks may be attributed not only to the effects of the exposed granite bodies, but to subjacent bodies as well. Their coincidence with areas of intense regional deformation, similar to conditions noted by Barrell in Connecticut,[13] tends to confirm Keith's conclusion that the pressure that induced the deformation was supplied by the intruding granite.[14]

The writer concludes that the granite areas in the Columbia quadrangle, as well as similar areas throughout Piedmont South Carolina, represent only exposed cupolas and stocks extended from a subjacent regional batholith that has affected the roof rocks generally. In the Smyrna gold mining district, 35 miles to the north of the Columbia quadrangle, the writer has found that, in addition to large granite areas intruded into another portion of the "slate belt," the granite has soaked its way upward in many minor localities, and has broken through bodily in some. The evidence of a major and comparatively shallow source of the granitic material that permeated the "slate belt" is very striking in this district.

As may be seen in Figure 1, there is noticeable deflection of regional strike about the large granite mass in the northern part of the quadrangle. This deflection is most pronounced to the north of the mass where these well-defined effects of granitic intrusion extend for miles into the older rocks. The less affected rocks lie to the south of the mass, and preserve the more normal regional strike rather uniformly except in the vicinity of the small, elongate granite mass 8 miles northwest of Columbia. Detailed mapping of strikes and dips of the "slate belt" and of the structure and texture of the granite would doubtless yield considerable data on the mode of emplacement of the granite. From the general work done so far, the largest granite mass is found to be oriented distinctly across the original strike, which it has modified as noted above, but it is not known whether it forms a cross-cutting stock or a composite, sill-like mass

[13] Joseph Barrell, "Relations of Subjacent Igneous Invasion to Regional Metamorphism," *Amer. Jour. Sci.*, 5th ser., Vol. I (1921), p. 14.

[14] "Outlines of Appalachian Structure," *loc. cit.*, pp. 315, 365.

that dips northwest and has locally domed or otherwise flexed the overlying beds. Regardless of its exact form its structural relations imply the exertion of considerable displacing action by the intruding mass, even though the effects of that action have been obscured by injection and replacement.

The original strike and dip have clearly exerted some influence on the intrusion of the granite, as may be seen in the general alinement of certain boundaries of the mass, and in the structural details of most outcrops in the marginal zone. In this zone, the strike of the older rocks is found to have governed injection and replacement, as will be described later, yet this process, as has already been stated, seems to have weakened the older rocks sufficiently to permit general warping of the strike. Therefore, while the intrusion as a whole seems to have been transgressive, its marginal extensions have been almost entirely along the strike of the border rocks.

INJECTION AND REPLACEMENT OF THE PRE-GRANITE ROCKS

Slaty cleavage is known to cross the bedding at various angles throughout the southeastern "slate belt," particularly where bedding is well preserved and not very steep. This feature has been identified in only one locality in the Columbia quadrangle, about 2 miles south of Little Mountain. With this exception, the original bedding has a consistently steep dip, and, where it has been recognized, slaty cleavage and schistosity coincide with it. From the comparatively little-metamorphosed tuffaceous and argillaceous rocks in areas remote from granite, the pre-granite rocks grade into their recrystallized, schistose equivalents nearer the intrusive masses.

Even where their original bedding may still be clearly recognized, the salic members are found to have recrystallized, with their more platy minerals mostly elongate parallel to the bedding planes. Their dominant minerals are sericite, quartz, biotite, and plagioclase. Of these only part of the quartz and part of the plagioclase constitute original clastic grains or crystals. The sericite forms felty mats, is generally dispersed through the rock, and shows a tendency to fill irregular seams as well as regular, rather continuous bands parallel to the bedding. The original quartz grains are usually larger and more clearly defined than those of the infiltrated silica which form micro-

scopic bands and irregular veinlets in addition to their general dissemination in the groundmass. The original quartz is usually less abundant than the secondary. Both varieties commonly show strain shadows. Biotite is scarce in the salic rocks farthest from the granite, but with approach to the intrusive masses it becomes increasingly abundant in extremely fine flakes. Similar early development of biotite due to granitic influence was noted by Harker and Marr[15] in the work previously cited. Plagioclase is a rather persistent, if not abundant, mineral, and also comprises both primary and secondary grains. The primary plagioclase is usually ragged, broken, and well impregnated with sericite and epidote. The secondary grains are comparatively large but free from granulation and chemical alteration, and lie both oblique and normal to the bedding or foliation. They have made room for themselves partly by crowding the micaceous laminae apart, and partly by replacement of the finer-grained material. Epidote and chlorite are rather minor accessory minerals in the less metamorphosed of these salic rocks, the epidote derived chiefly from original plagioclase, and the chlorite from secondary biotite.

As the salic rocks are traced still nearer to the granite, recrystallization becomes more pronounced. Biotite increases greatly in quantity and in the size of the individual flakes. Thin sections reveal the addition of microcline and microperthite in irregular to roughly rectangular, non-oriented crystals that show little or no strain. As these crystals increase in quantity, the rock becomes less schistose and assumes a granitic composition, especially as seen in thin section. With the appearance of these replacing feldspars, there are frequent occurrences of pods, stringers, and layers of physically injected granitic material along certain foliation planes. Apatite, magnetite, and occasional zircon are developed in the coarsely crystallized rock near the granite. Strike and dip, with minor undulations, remain the same throughout the process.

Most of the mafic members of the older rocks become less schistose than the salic members upon recrystallization before injection, because of their large content of hornblende instead of mica. Intermixed with these hornblendic rocks, there are less numerous mem-

[15] *Op. cit.*, pp. 304, 307, 308.

bers that have developed biotite where considerably influenced by granite. Both hornblende and biotite are dominantly oriented with the foliation, but, in thin sections, biotite may frequently be found to lie across it. From observations made throughout the quadrangle and the surrounding region, it is believed that both hornblende and biotite have originated mainly from the further recrystallization of members that had already been altered to chlorite-schists, although it may be that a few members were converted directly from their original character into hornblendic and biotitic rocks. In the hornblendic members, micas, though present, are so subordinate that the resulting schist has a linear rather than platy structure. Bedding is preserved in sharp, parallel planes that separate layers of distinctly different mineral composition, and are far too prominent to be confused with foliation. The sedimentary origin is better preserved in the dominantly mafic than in the salic zones because of their greater diversity in composition. At frequent intervals, ranging from a few inches to several feet, salic beds are interlayered with the dominant chloritic or hornblendic and biotitic members.

Besides hornblende, biotite, and chlorite, the mafic members contain considerable plagioclase of both primary and secondary origin, as well as epidote which forms thickly to thinly disseminated, comparatively large, irregular grains and also irregular to lenticular clusters of very small grains. Quartz, both original and infiltrated, is a constant component, and varies in amount as it does in the salic rocks. It usually shows strain shadows. Sericite is present in minor amount, and is derived from the original plagioclase. Apatite and magnetite, in the mafic as well as the salic members, appear where the rocks are definitely influenced by the granite. As the mafic rocks are traced from the simply recrystallized areas toward the granite, the foregoing minerals become more definite, cleaner-cut, and coarser-grained until the presence of replacing magmatic material is observed. From this point, as in the salic rocks, replacement by microcline and microperthite progresses rapidly with coarsening of the hornblende and biotite. A little chlorite, derived from biotite, is observed both parallel to and across the foliation. Its mode of occurrence is similar to that of the muscovite that has been developed from sericite in the salic zones, but this late chlorite of the mafic

zones is of minor importance, while its equivalent muscovite of the salic zones becomes dominant. Strike and dip in the mafic as in the salic rocks have been largely unaffected throughout the process.

The resultant gneisses or highly injected and replaced schists bordering the granite have the mineral composition of the granite itself. The original rock has been so impregnated by increasing amounts of microcline and microperthite that it has become as granitic as the truly intrusive layers, and the rock may be aptly termed a replacement granite. This replacement granite is characterized by the inheritance of platy ribbons of biotite or the linear and rather regular arrangement of hornblende. In isolated outcrops, the arrangement of biotite and hornblende may at first suggest either dynamic deformation of the granite or original flow structure; but the microscope reveals no granulation of microcline and primary quartz that would result from deformation, and clearly shows that the microcline and secondary quartz envelop and impregnate the original minerals of the schist. Granites with similarly inherited structures have been described elsewhere.[16]

As the writer's original objective was to outline areas in which granite of architectural and monumental grade might be found, the boundary of the large granite mass in Figure 1 has been drawn accordingly. Detailed mapping to show the distribution of injection and replacement effects would call for much more time and a base map of much larger scale. Even in the work done, however, the effects of injection and replacement could be traced as much as 4 and 5 miles away from the granite borders as mapped. Where these effects are so continuous, it seems more likely that they reflect the downward widening of granite masses, and the injection and replacement of rock above the concealed portions, rather than the essentially horizontal penetration of granitic material for such long distances from the present exposures.

[16] C. N. Fenner, "The Mode of Formation of Certain Gneisses in the Highlands of New Jersey," *Jour. Geol.*, Vol. XXII (1914); E. S. Larsen and F. K. Morris, "Origin of the Schists and Granite of the Wachusett-Coldbrook Tunnel, Mass.," *Geol. Soc. Amer. Bull. 44* (1933), abst., pp. 92–93; W. M. Agar, "The Granites and Related Intrusives of Western Connecticut," *Amer. Jour. Sci.*, 5th ser., Vol. XXVII (1934); A. L. Anderson, "Contact Phenomena Associated with the Cassia Batholith, Idaho," *Jour. Geol.*, Vol. XLII (1934), p. 376.

In summary, the Columbia quadrangle and surrounding area contain numerous bodies of granite that have been intruded into the "slate belt," which dips steeply northwestward with widespread development of schistosity parallel to the bedding. The most remote direct effect of the granite on these older schists is hydrothermal recrystallization. As the granite is approached, injection and replacement by the magma are found to have occurred with increasing effectiveness. Where the injection and replacement of the wall rocks has been carried to completion, the granite is enriched in some localities by biotite-rich wall rocks, in others by hornblende-rich wall rocks, whereas in others the composition of the granite is not materially affected. There has been simply a union of the constituents of the two rocks with slight to considerable elimination of the original constituents of the invaded rocks. This process, together with stoping, has enabled the granite progressively to extend a border zone through which it has absorbed or assimilated the older rocks. All border differences in composition observed by the writer in and near the Columbia quadrangle may be directly attributed to the wall rocks.

A BASAL CAMBRIAN LAVA FLOW IN NORTHERN VIRGINIA[1]

A. S. FURCRON AND HERBERT P. WOODWARD

ABSTRACT

An amygdaloidal and porphyritic lava flow occurs at the base of the Lower Cambrian series along the west slope of the Blue Ridge in northern Virginia. This flow, which is here described from exposures between Luray and Port Republic, rests upon either the pre-Cambrian Catoctin greenstone or hypersthene granodiorite. It is overlain by, or grades into, the basal beds of the Loudoun formation of early Cambrian age.

GENERAL STATEMENT

The presence of a purplish-red, slaty, lava flow immediately below the Lower Cambrian sediments was discovered by the writers in 1932 during a geologic survey of the Stony Man quadrangle, which

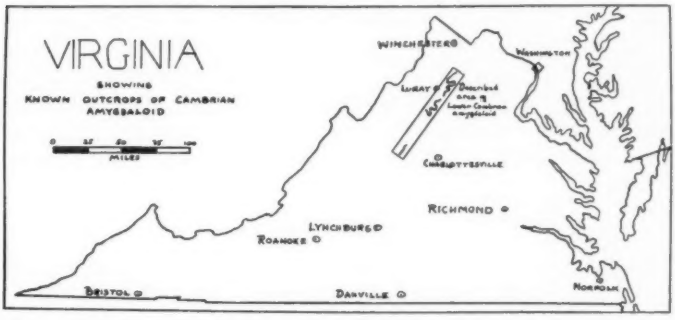

FIG. 1.—Outline map of Virginia, showing the known outcrops of basal Cambrian lavas and the areas of occurrence described herein.

includes a portion of the west side of the Shenandoah National Park area in northern Virginia.[2] The flow is exposed at many places along the western slope of the Blue Ridge between Rileyville and Stanley in Page County, where the elevations of its outcrops range from the level of Page Valley, 1,100 feet above sea level, nearly to the crest of the Blue Ridge, some 3,000 feet higher (Fig. 1). From its proximity

[1] Published with the permission of the state geologist of Virginia.

[2] Manuscript in files of the Virginia Geological Survey.

and superficial resemblance to the Catoctin greenstone, as well as from an obscure topographic position, the Paleozoic extrusive has escaped previous recognition in this region.

The exposed ledges of the amygdaloid are rather inconspicuous at the point where the flow was first observed along the western slope of Hoak Hill, 7 miles southeast of Luray, in Page County. Additional and more diagnostic exposures, however, have been examined as far north as Rileyville, and an analogous extrusive rock is known to occur at a similar stratigraphic position in the Blue Ridge south of Stanley. Although the rock is not universally present along the western slope of the Blue Ridge, nevertheless it may be observed at many localities where the pre-Cambrian–Paleozoic contact is accessible (Fig. 2).

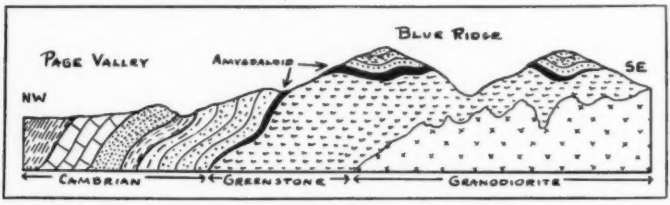

Fig. 2.—Generalized section showing the present position of the basal Cambrian flows.

This portion of the Blue Ridge involves a complex of massive igneous rocks of pre-Cambrian age. These crystalline rocks are overlain by arenaceous Lower Cambrian sediments, and all have been contorted and subjected to strong deformation. The Cambrian sandstones stand in the foothill belt with highly inclined dips toward the northwest. The lava flow rests unconformably upon the Catoctin greenstone or, in a few exposures, upon a coarse hypersthene granodiorite, both of which are of pre-Cambrian age. The Catoctin greenstone consists of a thick mass of lava flows, mostly of metabasalt. Throughout much of northern Virginia, where it forms the crest of the Blue Ridge, it is usually massive and resistant. The greenstone derives its color largely from epidote, which is a common alteration product of the basalt. In Virginia, the Catoctin is a much-

altered basalt which is commonly amygdaloidal but is rarely porphyritic.

The hypersthene granodiorite,[3] which is a widespread intrusive igneous rock of the northern Blue Ridge Province, is massive and generally coarse grained. It is dark or greenish gray, and carries abundant feldspar, quartz, and hypersthene or other femic minerals. Furcron believes that it is intrusive into the Catoctin greenstone and, accordingly, that it is of later pre-Cambrian age than the greenstone. Unakite and pink epidote-bearing granite are frequently found in this region at, or near, contacts of intrusives with the Catoctin greenstone. In Cubbage Hollow, south of Stanley, where the amygdaloid is present at the base of the Lower Cambrian sediments, it rests unconformably upon pre-Cambrian unakite.

The Loudoun formation, which constitutes the earliest Paleozoic sediment of this region, is an aggregate of sandstone and shale. It is essentially dark colored, arenaceous, and medium bedded. Some of the sandstone members are arkosic and are commonly dark reddish purple. The shaly beds have been mildly metamorphosed and in places approach phyllites in character. They are somewhat lighter in color than the sandstones, and are either silvery in appearance or are slightly bluish. There is no widespread conglomerate at the base of the Loudoun to correspond with the strong pebbly zone at this horizon in southern Virginia and Tennessee.

CHARACTER

The amygdaloidal lava flow at the base of the Loudoun is generally reddish brown or dark brown. A few exposures show a chocolate-colored rock; at other points, the material superficially resembles the reddish shales of the Waynesboro formation of early Cambrian age. The flow is variable in thickness and is locally absent—a fact which indicates that considerable erosion followed its extrusion and preceded the initial Cambrian sedimentation.

Several localities exhibit the flow to good advantage. A wide outcrop surrounds Knob Mountain, 8 miles northeast of Luray; and exposures in this belt are visible along both valley walls of Jeremy

[3] Anna I. Jonas, "Hypersthene Granodiorite in Virginia," *Geol. Soc. Amer. Bull. 46* (1935), pp. 47–60; A. S. Furcron, "Igneous Rocks of the Shenandoah National Park Area," *Jour. Geol.*, Vol. XLII (1934), pp. 400–410.

Run, 1 mile east of Vaughn. The rock is exposed at the base of the Cambrian section along Lee Highway, 6 miles east of Luray and 1 mile east of Pumpkin Hill, as well as in the slopes behind Hill School. Another exposure, near Blaineville, is crossed on the western flank of Hoak Hill by the road which leads southeastward from Stony Man village. Deep, narrow, isolated recesses, including Basin and Cubbage hollows, have been eroded into the west foot of the Blue Ridge south of Stanley, and exhibit the lava flow at the base of the Paleozoic group. A good exposure occurs in Lucas Gap on Tanners Ridge, between Basin Hollow and the valley of Hawksbill Creek.

The amygdaloid has been traced in a discontinuous belt from a point east of Rileyville nearly to Brown's Gap at the junction of Albemarle and Rockingham counties. Mashed, slaty facies of this rock are well exposed along the road west of Simmons Gap in Rockingham County. No exposures of the flow, however, have been observed on the eastern slope of the Blue Ridge, nor is it known definitely to underlie the outliers of Loudoun which are separate from the sediments of the foothill belt.

In the Luray region the rock is non-porphyritic but commonly contains amygdaloidal vesicles that are usually filled with white or pink quartz. Fillings of epidote, which are characteristic of the Catoctin amygdaloids, are rare or absent in the Cambrian flows, where the amygdules are smaller than those of the Catoctin amygdaloids. Hand specimens of the fresh rock are either dense or slaty. Upon weathering, the flow disintegrates readily to form a soft clay soil in which few fragments of solid rock occur. In deeply weathered cuts it is difficult to find any fresh specimens of the amygdaloid. Wherever the rock has been strongly crumpled, a slight cleavage is present and the amygdules are crushed flat. In general, however, the Cambrian flow beds are less metamorphosed than those of the Catoctin greenstone.

Along the western side of the Blue Ridge, southwest of Luray, a green schistose rock locally occurs at this horizon. This material, which is distinctly porphyritic, is also found east of Elkton.

At the top of the Blue Ridge, on the western side of Big Flat Mountain, near the junction of Greene, Albemarle, and Rockingham counties, the porphyritic facies is extensively developed. In hand specimen the rock lacks epidote, is gray green in color, and is

finely schistose. It exhibits the moderate metamorphism which is characteristic of the Lower Paleozoic sediments of the region, and contains large, rectangular, feldspar phenocrysts that reach 1 inch in length and ½ inch in diameter. Some of the feldspars are crushed into flat, light-gray masses. Where less strongly mashed, they are gray or greenish gray in color, and do not exhibit polysynthetic twinning. Where they have largely escaped crushing, the feldspars are little altered from their original condition, although there is some alteration to calcite. Several of these phenocrysts which were examined showed indices of refraction between 1.558 and 1.565.

In Cubbage Hollow, southwest of Stanley, the flow varies between 0 and 200 feet in thickness. It is not present on the western side of the hollow where the basal members of the Loudoun rest directly upon the granodiorite. On the eastern side of the hollow, a short distance away, the amygdaloid has a thickness of at least 150 feet and immediately overlies granodiorite and unakite.

Near Lucas Gap in Basin Hollow, the flow has been partially reworked into sediment; and it apparently grades directly upward into the lowest members of the Loudoun formation. The Catoctin greenstone beneath the flow is massive at this exposure, and contains several zones of a purplish amygdaloid which is rich in epidote. In the initial examination of the exposure, all of the amygdaloidal material was tentatively assigned to the greenstone. It was not until the amygdaloid was found directly over granodiorite and under Lower Cambrian sediments that the true age of the flow could be demonstrated.

In the vicinity of Bailey's Store, 2 miles south of Stanley, the basal Cambrian sediments are largely composed of re-worked volcanic materials which superficially resemble red slaty varieties of the flow rock. This type of sediment may be well studied in an outlier 1 mile northeast of Bailey's Store, where hand specimens of the rock contain grains of quartz and feldspar that were introduced from the old intrusives during the re-working of the material. In places this sediment is interlayered with beds of normal sandstone and shale.

An interesting but somewhat inaccessible exposure of the basal Paleozoic contact occurs below Franklin Cliffs at the head of Little Hawksbill Creek, 5 miles southeast of Stanley, at an elevation of about 2,500 feet above sea level. The creek falls from ledges of

greenstone across a narrow outlier of Loudoun sediment in which the Cambrian arkoses lie at the contact of greenstone and granodiorite. The lowest Paleozoic unit is a coarse conglomerate which contains fragments of both types of pre-Cambrian igneous materials, as well as unrounded fragments of the amygdaloid.

Microscopically, the flows usually show a fine felt-like groundmass of sericite with other secondary minerals. There is much red iron oxide, which is responsible for the prevailing color of the rock. No feldspar phenocrysts appear in thin sections that were examined from exposures near Luray, although there are numerous elongated, rectangular minerals that have been altered to sericite. Little epidote is present, and the flow appears to be less basic than the Catoctin greenstone.

In the absence of chemical analyses, it is not safe to attempt an exact classification of this rock. Its usual physical appearance is suggestive of a vesicular rhyolite, but it is probably more femic than a true rhyolite and more salic than the Catoctin metabasalts. The absence of epidote is notable. Through the introduction of secondary minerals and subsequent metamorphism, the flow has become altered to a slaty rock in which flow structures, such as banding, are rarely encountered. The rock does not remain uniform in character when traced along the line of strike. Southwest of Elkton, where it is locally sericitic, its color is similar to certain facies of the Loudoun formation.

As it is less resistant than the igneous rocks beneath and the sediments above, the flow produces no distinctive topography or soil; and its presence can be determined solely upon the identification of amygdaloidal material.

INTERPRETATION

This volcanic rock is assigned to the Lower Cambrian. It occurs most commonly between the earliest sediments of the Paleozoic and the Catoctin greenstone. It has been found, however, above granodiorite in the absence of any greenstone—a fact which strongly suggests that the extrusive is later or younger than either the greenstone or granodiorite. Indeed, no other interpretation is possible except to identify the amygdaloid with the greenstone in apparent contradiction to the lithologic and stratigraphic evidence. Small, narrow,

linear inclusions of red, slaty volcanic rock likewise occur within the area of the Catoctin greenstone in the same manner as do similar outliers of Lower Cambrian sediments. This mode of occurrence suggests that the surfaces of both greenstone and granodiorite were irregularly eroded before the Cambrian sediments were deposited or the amygdaloid extruded. Probably the erosion which preceded the extrusion of the flow was sufficient to penetrate the Catoctin greenstone, and to expose, at one locality at least, the invading granodiorite.

Some of the small, isolated patches of basal Loudoun are largely composed of fragments of slaty amygdaloid. This condition appears to be present both in the sediments along the foothill belt west of the Blue Ridge and in some of the sedimentary outliers within the Blue Ridge Province. It is probable that considerable amounts of the amygdaloid were eroded from this region before the initial Cambrian sediments were deposited, and the total absence of the flow in some localities points to an erosion interval following the early Cambrian volcanism.

Evidence presented above seems to indicate an early Cambrian age for the volcanic rock in question. In other areas along the Blue Ridge, amygdaloidal material is also known to occur either within, or at the base of, the Loudoun, or its equivalent, the Unicoi formation. An amygdaloidal bed has been reported near the base of the Unicoi east of Front Royal, and also on the Rock Fish Gap road southeast of Waynesboro.[4] Similar beds are now known to occur within the Unicoi in other parts of the State, as well as in the type locality of the Unicoi in northeastern Tennessee, where volcanic material occurs with the early Cambrian sandstones.

The presence of extrusive volcanic rocks at the base of the Cambrian system indicates a renewal of volcanism at the beginning of the Paleozoic Era, although the volume of Paleozoic volcanic material is far less than that to be found within the pre-Cambrian rocks. It is probable that further search for this flow will uncover additional exposures in areas where it has so far escaped observation.

[4] G. W. Stose, *et al.*, "Manganese Deposits of the West Foot of the Blue Ridge, Virginia," *Va. Geol. Surv. Bull. 17* (1919), p. 13.

CLAY COLLOIDS AS A CAUSE OF BEDDING IN SEDIMENTARY ROCKS

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ABSTRACT

Colloidal clay of the montmorillonite-beidellite group extracted from the Putnam soil of Missouri was studied under the petrographic microscope while undergoing flocculation. The floccules were relatively coarse aggregates so well oriented as to resemble crystals. They were platy in shape, resembling in that respect the mineral in a bedded clay shale.

It is suggested that bedding in shale may originate in part in the colloids contributed to it, that clay may be carried far seaward as a colloid and be flocculated and deposited in coarser floccules, and that clay partings and films in limestone may originate from flocculated clay colloids. The texture of fire clays is contrasted with that of shale.

INTRODUCTION

A recent study of the bedding of sedimentary rocks and work with soil colloids indicate strongly that colloids may play a more important part in the development of bedding and lamination of shales and other sediments with an argillaceous content than has hitherto been recognized.

A typical marine shale, particularly a clay shale, in thin section (cut at an angle to the bedding) shows under the microscope a degree of parallelism of structures as prominent as that usually seen in the outcrop or hand specimen. If the thin section is examined between crossed nicols of a petrographic microscope it will show, as the stage is turned, alternate extinction and illumination so uniformly that 80 per cent or more of the particles may appear to be oriented optically parallel. In this connection Ross states, "Some beidellite shales extinguish under crossed nicols almost as sharply as a mica, and in fact have the appearance of a light-colored biotite crystal."[1] Elongation of the shale minerals is positive. The short axes of the crystals, and in this case also the direction of the low index of refraction, are alined, although the other indices need not necessarily be so. It follows, therefore, that the bedding of clay shales is due

[1] C. S. Ross, "The Mineralogy of Clays," *Proc. 1st Intl. Cong. Soil Sci.*, Vol. IV (1928), p. 559.

primarily to mass orientation of the constituent particles. It is similar mechanically, but not genetically, to the orientation of particles seen in a section cut normal to slaty cleavage, or the schistosity of mica-schists.

This orientation of particles in shale has been observed long ago and is recorded in the handbooks on petrography, but the description is repeated here, however, for those interested in sedimentary rocks whose training has not included microscopic examination of the shales in thin section.

Before discussing the origin of the orientation of clay particles it should be stated that the effect of change in particle size, composition, or color on the development of bedding or lamination is also duly recognized. This discussion, however, is restricted to the cause and effect of orientation.

EXPERIMENTAL WORK

The explanation of the lamination in shales is that fine, platy flakes of mica, chlorite, or some clay mineral, and needles of linear elongate particles are carried out by waves or currents to a place where the water is sufficiently quiet that they may settle out and come to rest with their long dimensions parallel. It has been held by some that colloidal material carried out or flocculated with the larger particles comes to rest with them and acts as a paste cementing the crystals together. This may be true in part, but it will be conclusively shown, further, that colloidal clay sols upon desiccation give rise also to crystalline aggregates having a high degree of orientation resembling that of the clay mineral in shale. In other words, the lamination of shale may be developed from deposition of colloidal clay.

It is noteworthy that the clay colloids with which these effects have been observed are those derived from soils, an important source of sedimentary rock material. The colloidal clays studied by the writer were soil-derived sols prepared by the Soils Department of Missouri University from the Putnam silt loam of northeast Missouri and from two soils of North Carolina. Later, while searching through the literature, it was found that Hendricks and Fry[2] had

[2] Sterling B. Hendricks and William H. Fry, "The Results of X-ray and Microscopical Examinations of Soil Colloids," *Soil Sci.*, Vol. XXIX (1930), pp. 457–79.

studied other soil colloids with similar results, and that Grim[3] had described a technique for studying disaggregated shales and clays from suspension of particles slightly larger than colloids which, however, would be applicable to sols.

The writer's first study was on the clay of the Putnam colloid, extracted by the method developed by Bradfield,[4] and shown to belong to the montmorillonite-beidellite group by X-ray powder photographs,[5] optical properties,[6] and chemical analysis.[7] Verification of the extreme fineness[8] of the particles in the sol at the time of study was made by focusing on the sol using 1200× magnification in the microscope. No particles were visible.

In addition, observation of the mount was continued, using a magnification of about 150 diameters, while evaporation of the water and flocculation of the colloid took place.

To the surprise of the writer, flocculation of the isotropic sol did not result in the formation of an isotropic film, but instead, there appeared strikingly anisotropic aggregates, optically continuous in themselves, and covering a third to a half of the microscope field on the water side of the water-air interface.

Adjacent to any one of these aggregates might be another aggregate at a different orientation. They were best observed with nicols crossed and with the first order red gypsum plate in the system. Evaporation was slow and no evidence of movement (currents) which might orient the particles to give this effect was apparent. It appears that during flocculation the many colloidal particles (probably each crystalline in itself, cf. X-ray pattern) orient themselves one to another in such a manner that the atomic space lattice of the particles at the floccule nucleus is extended, presumably in regular

[3] R. E. Grim, "A Petrographic Study of Clay Minerals—A Laboratory Note," *Jour. Sed. Petrology*, Vol. IV (1934), pp. 45–47.

[4] Richard Bradfield, "The Use of Electrodialysis in Physico-Chemical Investigations of Soils," *Proc. 1st Intl. Cong. Soil Sci.*, Vol. II (1928), pp. 858–68.

[5] Personal communication from Professor L. D. Baver, Soils Department, University of Missouri.

[6] The writer.

[7] Richard Bradfield, "The Chemical Nature of Colloidal Clay," *Jour. Amer. Soc. Agron.*, Vol. XVII (1925), pp. 253–70.

[8] Reported as being .1 micron and less in diameter by Professor L. D. Baver.

order, through those building on. This simulates the growth of a crystal, except that large colloidal particles add to the nuclear group instead of ions or molecules in solution.

However, orientation within the aggregate is either not perfect or else impurities are included in it, because there is some variation in the optical properties of the flocculate. The indices approximate 1.56, the birefringence .020, and 2V varies from about 0° to over 30°. Optical character was always negative with the Putnam sol. These values, and also variations, are in accord with Hendricks' and Fry's[9] results. The variations are of interest, particularly in view of some evidence that points toward a correlation between them and the nature of the cation in the base-exchange complex. Since that problem is being worked on in connection with additional soil investigations, specific optical data are omitted here. The two high indices of refraction and the axial angle can be determined on the flat-lying residue of a dried drop of sol on a microscope slide, but the other index normal to the flake is easiest measured on fragments obtained by crushing a larger dried quantity in mortar. It is remarkable how closely these flocculation aggregates resemble an orthodox crystal. In light of the statement by chemists that it is common for substances to pass through a colloidal state from the molecular to the solid upon high concentration, it seems probable that many crystalline minerals may be formed from a colloidal transition state. In particular, if a clay colloid had the composition of beidellite, then normal crystals of beidellite might result from its flocculation. At any rate, the evidence points toward the possibility of the formation of clay shales having a laminated structure from colloids derived from weathered soils. That the action is reversible is shown by Grim's[10] work.

A few observations were made on the colloid of the Davidson soil of North Carolina, a type whose composition tends toward the lateritic. Only slight orientation of the particles was present in the dried residues. Such a result, however, would be expected, since the constituent minerals of the beidellitic and lateritic soils differ vastly from each other in shape and composition. It would be of interest to

[9] *Loc. cit.* [10] *Loc. cit.*

study, if such exists, a shale of laterite composition, derived with little contamination from a laterite source.

Likewise, a geologic study supplementing the meritorious work of Mattson[11] on soil weathering and the formation of iso-electric precipitates of colloidal silica and aluminum hydroxide—synthetic "clays"(?) having silica-alumina ratios correlative with the acidity of the environment, as in weathering—should be of interest and value. It is unfortunate for the geologist that optical and X-ray studies were not made on Mattson's materials to establish unquestionably the atomic pattern in them, and to demonstrate the degree of similarity to natural clays. Whether colloidal silica and colloidal alumina can be carried to the sea, be precipitated iso-electrically, as Mattson did in the laboratory, and form a crystalline clay mineral upon aging is a question whose needed answer still lacks positive confirmation. Its relation to bedding will be apparent.

GEOLOGICAL IMPLICATIONS

The writer believes that the observations on the flocculation of the colloids in this simple experiment introduce evidence which admits for the origin of some features of sedimentation a simple explanation which has not been clearly stated heretofore.

First, lamination and bedding may develop in the colloidal fraction of sediment making up part of a shale as well as in the coarser fractions. An accumulation of platy aggregates, like those formed experimentally, piling on top of each other would give rise to a laminated shale as seen in thin section. Hence, bedding in shale may be developed within the fraction contributed as a colloid.

Second, a mechanism is indicated by which a shale-producing material may be carried very far from shore and then deposited in aggregates or grains larger than the particles in which it was carried—the transportation of clay in the colloidal state. Brownian movement or the feeblest currents will keep the clay in suspension; therefore strong, bottom-scouring storm waves need not be appealed to in order to shift it seaward for long distances. Moreover, the aggregate formed after flocculation may be too large to have been shifted as a

[11] Sante Mattson, "The Electrokinetic and Chemical Behavior of the Alumino-silicates," *Soil Sci.*, Vol. XXV (1928), pp. 289–311; "The Laws of Soil Colloid Behavior," *Ibid.*, Vols. XXX, XXXI, XXXII, XXXIII, XXXIV.

single particle to its distant position. Thus, the origin of shales whose constituent particles appear abnormally large for their location is rationalized, and an explanation is given for their deposition great distances from shore.

Lest overemphasis be placed on long transportation of the clay as a colloid, it should be stated here that all colloidal clay brought to a saline sea is not expected to be carried far from shore. Much, or most of it, will be flocculated upon contact with the sea water because of the high concentration of ions in the latter. Nevertheless, it is believed that some of the clay will remain dispersed for considerable time, regardless of the nature of the salinity of the sea—present composition, or a possibly limeless state in the past. Dispersion is to be expected because some one of the great variety of ions available during the history of the clay for adsorption in the complex should be stabilizing. For instance, the alteration products—first, of an almost innumerable variety of parent rocks exposed to the weathering action of a wide range of climatic conditions, and second, transported in a different chemical environment—may give rise to almost any type of clay. More specifically, sodium, potassium, hydrogen, calcium, or magnesium clays may be transported by streams in which are dissolved acids or various metallic sulphates, chlorides, or carbonates. Moreover, the strongly protective action of organic colloids derived from humus and other organic acids may operate to stabilize a sol of any of the types of clay complexes. That some colloidal clay is suspended and some is flocculated in salt solutions was verified by the writer in a study by the colorimetric method of the pH of shale suspensions in strong neutral NaCl and $CaCl_2$ solutions. After stirring in the solutions pulverized shale from a number of formations, it was found that some quickly flocculated, whereas some continued to be so turbid after standing in absolute quiet for 48 hours that colorimetric measurements could not be read, and cleared only after standing over a week. The sol which finds itself relatively stable in the sea will escape early flocculation and will be carried out until later flocculated, when it produces the results described before.

Suggested causes for flocculation are those which the chemist finds to be effective in the laboratory. They are an increased and excessive concentration of colloidal matter, introduction of an oppositely

charged colloid, the concentration of ions in the sea water exceeding the flocculation point for the colloid, or the introduction of a new flocculating ion. Temperature change in the water may indirectly bring some of these about. In cases where a protective colloid maintains dispersion of the clay, a neutralization or destruction of the protective action would result in flocculation. Chemical changes in the sea water such as are brought about by evolution of ammonia from decomposing organic matter, sulphate reduction, CO_2 solution, volcanic emanations, and increased salinity which affect the hydrogen-ion concentration of the water or the degree of hydration of the suspended colloid may cause its flocculation and deposition. Further, the deposition of a clay later might be dependent more upon development of conditions inducing flocculation than upon new or rapid influx of clastic material. In other words, the concentration or amount of colloidal clay may have been increasing for years until a time of either local or widespread flocculation, at which time the water is cleared. It is conceivable that there might be a more or less periodic cleansing of the water of its colloid content similar to the water clarification process produced artificially in the settling basins of our water plants.

Third, the origin of the thin, disconnected, patchy, undulatory clay partings and fine-grained clay films in the carbonate rocks is reasonably and logically accounted for as flocculated clay deposits carried out colloidally to the zone of carbonate deposition. The partings and films are too numerous, small in extent, and irregular in distribution to be thought of as bedding planes of significance, or to represent extensive differences of sedimentation. Yet their presence in considerable number requires some explanation which must be consistent with a localized, apparently haphazard deposition. It is plausible that the clay of the parting or film might have been carried in as a colloid and flocculated over a restricted portion of the sea floor because of a favorable local environment, or that it was flocculated in the waters above and then settled onto the floor by chance to the position where it is found. Either widespread bedding planes or irregular bedding may occur. The former indicates uniformity of water and depositional conditions; the latter, the opposite. No unusual or catastrophic method of transportation need be appealed to

in order to explain the origin of the thinnest of clay films in limestone (barely visible in thin section) or an increase in thickness to those easily seen. Either a more concentrated suspension or a greater depth of water cleared would give rise to a thicker layer of clay.

Although bedding in sandstones was not studied extensively by the writer, it seems reasonable that the deposition of clay might play a similar rôle in its formation as with bedding in limestone. However, since the particle size of sand is larger than that of clay, appeal need not necessarily be made to colloidal clay to account for its occurrence in sandstones.

Last, in contrast to the bedded shales, the commonly non-bedded fire-clays of the plastic, semiplastic, and semiflint types, show a radically different structure in thin section. Instead of being laminated, their microscopic structure, in similarity to the appearance of the hand specimen, varies commonly from a mosaic of very fine particles oriented at random to blocky or linear-blocky aggregates (composed of parallel-oriented fibers or flakes), which vary in size but are likewise oriented at random. A few fire-clays show a rudely bedded structure. Because of their usual lack of bedding it is to be presumed that fire-clays have a history that is different from shales, but an attempt to generalize widely on their origin on a basis of structure alone would be high folly. Nevertheless, the evidence is strong that the origin of fire-clay is dissimilar to that of a marine shale, and that the degree or grade of weathering in the clay-formation process was well along toward equilibrium under the conditions of acidity in situ. Further, evidence contradictory to these conjectures is not seen in the field as far as Missouri fire-clays are concerned. Additional discussion on the origin of those fire-clays is withheld because the Missouri Geological Survey has work in progress on them.

CORRELATION OF ZOARIAL FORM WITH HABITAT

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ABSTRACT

A study of zoarial form in the cheilostomatous *Bryozoa* has shown that a definite relationship exists between the various zoarial types and their habitat. A percentage estimate of the various zoarial types present in an early Cenozoic bryozoan faunule gives a moderately accurate conception of the conditions under which the matrix bed was deposited.

INTRODUCTION

The bathymetric conditions under which their matrix bed was deposited may be deduced from a study of Cenozoic cheilostomatous bryozoan faunules. In later Cenozoic deposits the determination of the bathymetric facies is comparatively simple, since the majority of the *Bryozoa* present are still living and their present habitats are well known. But in early Cenozoic deposits the determination of bathymetric conditions is not so simple, since the percentage of Recent *Bryozoa* in these beds is much reduced. In fact, the persistent forms probably owe their survival to the present day because they are generalized as to habitat and hence are of little use as bathymetric indicators.

Some general criterion is therefore necessary to obtain a bathymetric estimate in Lower Cenozoic formations. A study of zoarial form in present-day groups has indicated a definite relationship between zoarial form and environment. The writer believes that this relationship can be applied with great facility, by a non-specialist in the field, to determine some of the conditions of deposition of the sediments containing the zoaria.

The types of zoaria found in the Cheilostomata are reduced to the nine groups described in the succeeding paragraphs. The names given to these are derived from the principal groups in which the respective zoarial types are best represented.

It is true that within one genus, or even one species, there are zoarial types which fall into more than one of these groups; but in many cases this is due to adaptation of the species to different

bathymetric facies. For instance, a common Victorian species, *Caleschara denticulata* (Macgillivray), ranging from early Miocene to the present, occurs in either the eschariform or vinculariform zoarial types. The former is the type represented in shore débris along the Victorian coast, whereas the latter is the form obtained at depths of 30–200 fathoms in Bass Strait and off the South Australian coast. From numerous sources of evidence it is recognized that the Victorian early Miocene has a facies of much deeper water than the comparatively shallow-water early Pliocene deposits, and it is therefore not surprising that the vincullariform zoarium is exclusively found in the former series and the eschariform in the latter.[1]

ZOARIAL TYPES

Membraniporiform.—Unilaminate zoaria whose entire basal lamina is attached to the substratum. This type is adapted for life in the littoral and sublittoral zones. Its form and situation tend to counteract the to-and-fro motion of the bottom water, where the depth is much shallower than the wave base. This is effected by the zoaria's incrusting flexible algae and loose shells, which sway with the motions of the bottom water. Though mainly limited to the littoral and sublittoral zones, many forms extend to deeper waters but are there numerically unimportant.

Petraliform.—The basal lamina of the unilaminate zoarium is attached to loose and irregular substrata, such as coralline algae and sponges, by means of chitinous radicles in all Petraliidae except *Petralia* Macgillivray (*sensu stricto*). This type is adapted for life in a particular habitat in the littoral zone, but occurs most abundantly in the sublittoral zone, since the space between the basal lamina and substratum weakens its resistance to wave action. The petraliform type is, in the littoral zone, a supplement of the membraniporiform type which can only incrust smooth, solid substrata. A specialized type of petraliform zoarium is seen in *Petralia undata* Livingstone, 1926 (non Macgillivray), where the zoarium is fenestrate and the proximal zooecia produce numerous radicles which unite to form an attaching filament fastening the zoarium to the sandy bottom, to

[1] L. W. Stach, "Victorian Lower Pliocene Bryozoa, Part I," *Proc. Roy. Soc. Victoria*, N.S., Vol. XLVII, No. 2 (1935), p. 340.

which facies this form is restricted. Because of its structure, it has survived on sandy bottoms in fairly deep water affected by currents, the fenestrate zoarium offering less resistance to current action. Such a specialized case is the best type of bathymetric indicator.

Eschariform.—Zoarium bilaminate, foliaceous; attached to the substratum either by radicles or direct adherence. This type is adapted for life in sublittoral zones at depths of at least 10 fathoms. The zoarium is strongly calcified and usually has a rigid basis of attachment. It may extend to deeper water, but not to the littoral zone. A special adaptation for a sandy bottom habitat occurs in *Parmularia* Macgillivray, in which the zoarium develops a chitinous attaching filament from the center of its proximal margin and differs essentially from *Petralia undata* only in its lack of fenestration.

Reteporiform.—Zoarium attached, rigid, strongly calcified, and fenestrate. This type is adapted for life in regions where wave action and currents are strong, these factors being overcome by the rigidity and fenestration of the colony. The unilaminate convoluted zoarium of Reteporidae is heavily calcified and secondarily strengthened by successive layers of avicularia developed on the basal side, as shown by Buchner.[2] The large bilaminate fenestrate Adeonae belong essentially to this group, but here the rigidity of the zoarium is due to heavy secondary calcification of the frontal wall. This type is most prolific in sublittoral regions.

Vinculariform.—Zoarium attached, consisting of erect, rigid, subcylindrical branches. The narrow branches of the non-articulate colony are adapted for life in deep or sheltered waters where wave action is absent and currents scarcely active. This group typifies growth in quiet waters and should be distinguished from membraniporiform zoaria which incrust thin stems of algae and assume a superficial resemblance to the vincullariform type, as is particularly well seen in specimens of *Thalamoporella californica* Levinsen from Santa Monica, California. In transverse section, these pseudovincullariform types show remains of the algal stem or an axial cavity formerly occupied by it.

[2] P. Buchner, "Studien über den Polymorphismus der Bryozoen. 1. Anatomische und systematische Untersuchungen an japanischen Reteporiden," *Zool. Jahrb. Abt. Syst.*, Vol. XLVIII (1924), p. 155.

Cellariform.—Zoarium articulated, with subcylindrical internodes consisting of numerous zooecia. This type is adapted for life in the littoral zone where algae usually form the basis of attachment and the effect of wave action is overcome by the articulation of the long, narrow internodes. This type extends occasionally to greater depths.

Catenicelliform.—Zoarium of articulated internodes of few zooecia. This type is adapted for life in the littoral zone where wave action is strongly felt. The internodes consist of one or two zooecia, thus allowing the zoarium to follow the motion of the water with little risk of breaking the colony, because of its extreme flexibility. The earlier internodes of the zoarium are commonly attached by radicles to stems of red algae, the later branches becoming free.

Flustriform.—The chitinous zoarium, inherently flexible, is especially well adapted for a littoral habitat; but, having no calcareous supporting skeleton, it is incapable of preservation.

Lunulitiform.—Zoarium free, hollow-conical, the zooecia opening on the outer face. The actual mode of life of this type of zoarium has not been demonstrated and is the cause of much controversy.[3] The examination of a series of nearly two hundred specimens of *Lunularia* and *Selenaria* from Bass Strait corroborates the fact that they are in no way attached to a fixed substratum in adult life, since no radicles were observed on any of the specimens, though it is probable that *Conescharellina* has some form of either temporary or permanent radicular attachment. Their free mode of life prohibits their existence in the littoral zone where wave action is strongly felt; and from their present-day occurrences, they are restricted to sandy bottoms where current action is strong, their upper limit being about 15 fathoms.

Dartevelle[4] has shown that many lunulitiform zoaria of the early Eocene (Lédien) of the Belgian Basin have undergone fracture due to excessive current action, the fragments each regenerating a complete zoarium. The regenerated portions can be distinguished readily under a hand lens, and thus their presence in a deposit constitutes a good indication of contemporaneous strong-current action.

[3] S. F. Harmer, "Recent Work on Polyzoa," Presidential Address, *Proc. Linn. Soc. London Sess. 143* (1931), p. 150.

[4] E. Dartevelle, "Contribution à l'étude des Bryozoaires fossiles de l'Éocène de la Belgique," *Annales Soc. Roy. Zool. Belg.*, Vol. LXIII (1933), pp. 70–72, Pl. II, figs. 3–5.

ESTIMATION OF THE FACIES

The various zoarial types overlap their prescribed zones both by natural migration and artificial dissemination; but the vast majority of each type conforms to its stated habitat, and a percentage estimate of the types present in a given faunule would not be affected by such sporadic exceptions.

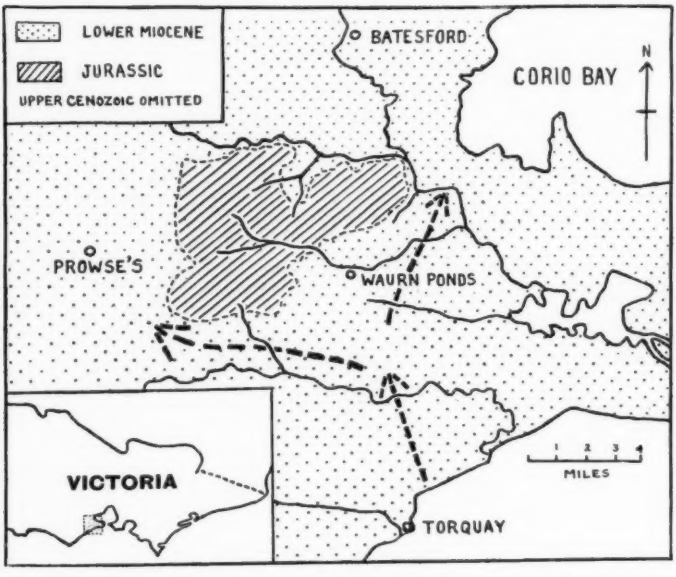

FIG. 1.—Illustration of the current trend in early Miocene times in the Geelong district (Victoria) as deduced from bryozoan faunules. The broken arrows indicate the current trends. The location of the area is indicated by the stippled portion in the inset map.

The stages in the estimation of the facies are: (1) the determination of the zoarial types present; (2) the determination of the predominating type or types; (3) consideration of any specialized types present. For work in the field, the first two alone could be employed and a conclusion could be reached in a short time by the examination of sievings taken from the deposit. The consideration of specialized types is essentially a laboratory study, and more specific data may

then be added to the general conclusions drawn from numerical estimates. A numerical estimate in this sense refers to the relative number of specimens of each zoarial type and not to the number of species in the sample conforming to the particular types.

A few examples may here be cited from Victorian Cenozoic areas with which the writer is familiar. In the Geelong Cenozoic Basin, to the southwest of Port Phillip Bay, there is a remarkable development of Lower Miocene bryozoan limestones overlying Upper Oligocene marls. The latter, exposed in the Torquay dome, contain an assemblage which is predominantly lunulitiform with minor catenicelliform and cellariform elements, from which it is concluded that the conditions during deposition were fairly shallow water (about 15 fathoms) with current and wave action. The Lower Miocene bryozoan limestones surround the Jurassic outlier of the Barrabool Hills, and samples were taken from exposures occurring around it. On the southeast side, at Waurn Ponds, the faunule is predominantly eschariform with fewer cellariform and lunulitiform types, the suggested facies, subjected to wave and current action, being about 20 fathoms. On the western side, at Prowse's quarry, the faunule has eschariform, reteporiform, and vinculariform types in about equal proportions, suggesting a quieter and slightly shallower facies. On the northern side, in the Batesford quarry, the faunule is predominantly vincullariform with minor cellariform and eschariform elements, pointing to a similar bathymetric facies but quite placid water conditions. The inference to be drawn from these data is that the Jurassic buttress deflected a general northerly current in early Miocene times and protected the lee side where the quiet-water facies is developed.

The early Pliocene faunule from Macdonald's locality at Hamilton, Victoria, recently investigated by the writer,[5] has lunulitiform, catenicelliform, and cellariform types in about equal proportion, with rarer eschariform and membraniporiform elements. From this it is inferred that the beds were deposited in fairly shallow water (about 10–15 fathoms) under the influence of currents and wave action.

[5] *Op. cit.*, pp. 338–51, Pl. XII.

DEPTH OF METEORITES AND GRADATION OF THE GREAT PLAINS

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Recently a 749-pound aerolite was discovered by the writer near Hugoton, Stevens County, Kansas. This large stone was found so near the surface of a level cornfield that its upper end had been encountered by the plow. The base of the meteorite was only 36 inches below the present surface level of the field. This is quite remarkable in the light of recorded witnessed falls.

Six individual aerolites of weights ranging from 50 pounds to 100 pounds have been recovered from witnessed falls. Their average depth of penetration was 32 inches. The falls of seven individuals weighing between 100 pounds and 200 pounds have been recorded. For these the average depth was 43 inches. Two individuals weighing between 200 pounds and 400 pounds have been seen to fall. These penetrated to an average depth of 48 inches. Three individuals weighing 400 pounds to 800 pounds have been recovered from an average depth of 122 inches.

The Hugoton stone is evidently of an ancient fall—probably centuries old. It was found where fluvial erosion would appear to be negligible, as the land is a level plain and the rainfall slight. There was no evidence of a local "wind blowout" although the whole region has been swept by dust-raising winds during almost the entire spring season. Dust storms are commonplace in the area.

It seems likely that the difference of 86 inches between the depth of the Hugoton stone and the average depth to which aerolites of comparable size have been known to penetrate probably represents, roughly, the amount of eolian degradation that had taken place since the Hugoton stone fell, probably a few centuries ago.

In making this suggestion the writer is fully aware that many important factors determine the depth to which a given meteorite will penetrate. Some of these factors are: (1) the velocity of the meteorite when it struck (whether the meteorite overtook the earth in its

flight around the sun or encountered it in a head-on collision),[1] (2) the nature of the soil and its condition (whether frozen, dry, or wet), (3) the form and specific gravity of the meteorite, (4) the angle at which it struck, etc. Of these factors only the nature of the soil is known for the Hugoton stone. In this case the soil is a light sandy loam to a depth of about 18 inches, below which it changes to a somewhat heavier dark mixture of sand and clay.

The Hugoton stone is the second largest stony meteorite that is known to have landed intact. Only the Paragould stone which fell in 1930 is larger. The third largest intact individual aerolite was the Estacada, Texas, stone (not seen to fall) which weighed 640 pounds. It was also found on the Great Plains and was exposed at the surface. This stone, however, lay on a narrow ridge and could have become exposed by the combined action of wind and rain.

Both the Melrose, New Mexico, and the Weldona, Colorado, aerolites were stones of more than 60 pounds in weight and both were plowed from level fields on the plains. Two of the Brenham, Kansas, meteorites weighed more than 460 pounds each and were so near the surface as to be struck by the plow. Several others of this fall which weighed from 200 to 300 pounds were plowed out. All were found in nearly level ground. The Brenham meteorites are of the stony-iron variety and their specific gravity runs about 4.5–5.0. Even an iron meteorite of 162 pounds was recently plowed up in the Brenham field, and another of about 190 pounds was plowed out in the South Dakota plains. None of these were of witnessed fall.

It seems probable that when more is known regarding the powers of penetration for various types and sizes of meteorites, and when we have completed a reasonably adequate survey to discover what meteorites lie within our reach and the rate at which alteration proceeds within them, here may be a satisfactory gauge by which to measure the rate of degradation or aggradation in a given region.[2]

[1] H. H. Nininger, *Our Stone-pelted Planet*, pp. 22–24; Farrington, *Meteorites: Their Structure, Composition and Terrestrial Relations*, pp. 19, 20.

[2] While the foregoing article was in press the Nininger Laboratory brought to light another large stony meteorite in Graham County, Kansas, weighing 623 pounds (fragments were missing which were estimated at 36 pounds). This stone was in the form of an angular block 35 by 25 by 13 inches. It lay in an almost horizontal position and reached a maximum depth of only 20 inches. The history of the field, the nature of the soil, and the apparent length of time since the meteorite's fall were about the same as in the case of the Hugoton stone. The field was slightly rolling.

GLACIAL PHENOMENA NEAR CRANBROOK, BRITISH COLUMBIA[1]

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ABSTRACT

Evidence is presented to show that, in the Cranbrook district, the Rocky Mountain trench and the lower reaches of its tributary valleys were not heavily eroded by the ice of the Wisconsin stage and that the ice sheet disappeared from the trench by stagnation and melting instead of by normal retreat. Both of these phenomena are commonly seen along the southern margin of the ice sheet in the United States but are in such marked contrast to what is observed over most of British Columbia, particularly near the coast, that they have so far escaped the attention they deserve in that province. The preservation of the rich Tertiary placers of the Cariboo and Cranbrook districts is due to limited erosion by the ice, so that the recognition of this condition elsewhere in the province may result in the discovery of other equally rich fields.

INTRODUCTION

The Rocky Mountain trench is a linear, slightly sinuous depression with a relatively level bottom extending from Montana to the Yukon and forming the western boundary of the Canadian Rocky Mountains and the eastern boundary of the Purcell Range. The town of Cranbrook is located about 40 miles north of the international boundary in the middle of the trench which, in this locality, is about 10 miles wide. The Purcell Range on the west rises to heights of 8,000 feet with a local relief of from 4,000 to 5,000 feet.

Moraines, which occur in great abundance, and grooving and striae, which mark many of the outcrops up to the highest elevation visited (7,725 feet), prove that the district has been entirely covered by an ice sheet of which the existing glaciers on the highest peaks are remnants. The prevailing southeast movement of the ice, indicated by the striae and grooving, suggests that the ice formed a vast continuous sheet rather than a number of isolated glaciers, while the freshness of the grooves, striae, and polish suggests that this continental ice sheet was Wisconsin in age.

INTENSITY OF GLACIAL EROSION

Over the greater part of British Columbia evidence of intense glacial erosion during the Pleistocene is unmistakable. It is some-

[1] Published by permission of the Director of the Geological Survey of Canada.

what surprising, therefore, to discover that the Cordilleran ice sheet in the Cranbrook district had only limited capacity for valley erosion.

Ice erosion during an epoch of glaciation in a mountainous area falls into two subdivisions, the first being that produced by the continental ice sheet as a whole, and second that produced by the individual glaciers during the alpine stage of glaciation which must follow the continental stage.

During the continental stage of glaciation in mountainous country the freest movement of the ice is in the upper portions of the sheet. It is therefore to be expected that erosion was most pronounced on the higher peaks. In the Cranbrook area this expectation is confirmed by the abundance of the southwest striae and grooving, which occur only on the rounded tops of the highest mountains.

During the alpine stage active erosion of the valleys is to be expected with the dissipation of the ice in the larger basins. Prominent cirques, cut into the flanks of the higher peaks, prove that erosion did take place at high elevations in the Cranbrook district during the alpine stage, but the following evidence suggests that glacial erosion in the trench and along the lower stretches of most of the valleys tributary to it from the Purcell Range was of only minor importance.

1. The usual cross section of these valleys is V-shaped instead of the normal U-shape of strongly glaciated valleys, and true hanging valleys are absent.

2. Placer gold occurs in much of the unsorted morainic material deposited along the lower courses of the streams flowing east from the Purcell Range, often in sufficient quantity to make extraction profitable. This gold must have been derived from pre-existing placers and the proportion of gold to glacial material suggests that it has been transported but a short distance by the ice. Furthermore, preglacial placers are still preserved in some of the valleys. Even on the supposition that the ice overran frozen auriferous gravels, its erosive power must have been very slight.

3. A large portion of the Rocky Mountain trench is underlain by a succession of unconsolidated silts, sands, and gravels 200–300 feet thick, the St. Mary's silts, which are known from stratigraphic and fossil evidence to be Miocene in age. Numerous moraines show

that the ice completely overran these sediments and yet carried off very little of the unconsolidated material.

4. In any heavily glaciated country unweathered minerals are found at the surface or within a very short distance of it, but in the Cranbrook district there are two notable exceptions: the Society Girl Mine and the North Star Mine. The outcrops near the Society Girl Mine, and its workings to a depth of from 30 to 40 feet, show a remarkable assortment of secondary minerals and practically no primary ore. A study of the outcrops of ore in the nearby deposits makes it clear that this secondary ore is a preglacial weathered remnant that has escaped removal. Secondary ore of a similar nature is also found in the North Star Mine.

These lines of evidence are taken to indicate that in the Cranbrook district, on the east slopes of the Purcell Range between the St. Mary's River and Moyie Lake, the Wisconsin ice was not a very active agent of erosion. This conclusion is in agreement with that of Johnston and Uglow, derived from a study of the Cariboo district. They state, "the narrow, V-shaped valleys were eroded only slightly by the ice"; and again, "what seems to have happened, however, in Bakerville area, is that during the great part of the period the area, except possibly on the uplands, was actually protected from erosion by the ice-sheet which was nearly stagnant."[2]

The southward slope of the trench is comparatively slight. The rate of movement, of course, depended on the slope of the ice surface rather than on that of the rock bottom, but there is no evidence to suggest a preponderant accumulation of ice to the north or south to make the slope at the surface of the ice differ from that at the bottom. The flow of the ice along the trench, therefore, must have been comparatively sluggish. At the same time, feeders to the main ice sheet from the Rocky Mountains on the east and the Purcell Mountains on the west probably supplied it with considerable quantities of material derived from the higher peaks. The low velocity of flow and the large load supplied by the feeders may therefore have combined to produce overloading and so account for the lack of erosion in the trench.

[2] W. A. Johnston and W. L. Uglow, "Placer and Vein Gold Deposits of Bakerville, Cariboo District, B.C.," *Geol. Survey Can. Mem. 149* (1923), pp. 27, 30.

The inability of the ice in the tributary valleys to erode importantly during the alpine stage needs a different explanation. The ice in the eastward sloping valleys, such as Perry Creek and the Moyie River, would have to move toward the ice in the trench, which may have been very thick even during the last stages of alpine glaciation. As a result, although the valleys themselves had a steep gradient, the slope of the ice surface would have been relatively slight and the movement consequently sluggish.

DISAPPEARANCE OF THE ICE

For many years the disappearance of all ice sheets was believed to have resulted from normal retreat. In 1898, however, Jefferson[3] suggested the stagnation of parts of the ice-front, and since that time the concept has been amplified and applied to various localities by many geologists. In 1929 Flint[4] summarized the existing ideas and presented new facts to show that the Wisconsin ice sheet, after it had pushed beyond the mountain barriers south of the St. Lawrence River, from the Adirondacks to Maine, became practically, if not entirely, stagnant and never regained motion.

It is believed that the ice disappeared from the Rocky Mountain trench in the Cranbrook district by such a process, a belief which is borne out by the close agreement of the following observations with Flint's criteria for dissipation by stagnation and melting.

1. Large kettles, often several miles in length, are common, indicating that the main body of the ice broke up into a number of separate masses of large size. This is one of the most important of Flint's criteria.

2. The moraines in many places show well-bedded, silty members and cross-bedded delta deposits, indicating that many small lakes were formed during the disappearance of the ice. While these are not unlike the lakes left by normal retreat of an ice sheet, they may be distinguished by their number, the great area covered by them, and the variations in the directions of their outlets. Flint suggests that these lakes formed along the margins of bodies of ice as they shrank.

[3] M. S. W. Jefferson, "Post-Glacial Connecticut at Turner's Falls, Massachusetts," *Jour. Geol.*, Vol. VI (1898), pp. 463–72.

[4] Richard F. Flint, "The Stagnation and Dissipation of the Last Ice-Sheet," *Geog. Review*, Vol. XIX (1929), pp. 256–87.

that the ice completely overran these sediments and yet carried off very little of the unconsolidated material.

4. In any heavily glaciated country unweathered minerals are found at the surface or within a very short distance of it, but in the Cranbrook district there are two notable exceptions: the Society Girl Mine and the North Star Mine. The outcrops near the Society Girl Mine, and its workings to a depth of from 30 to 40 feet, show a remarkable assortment of secondary minerals and practically no primary ore. A study of the outcrops of ore in the nearby deposits makes it clear that this secondary ore is a preglacial weathered remnant that has escaped removal. Secondary ore of a similar nature is also found in the North Star Mine.

These lines of evidence are taken to indicate that in the Cranbrook district, on the east slopes of the Purcell Range between the St. Mary's River and Moyie Lake, the Wisconsin ice was not a very active agent of erosion. This conclusion is in agreement with that of Johnston and Uglow, derived from a study of the Cariboo district. They state, "the narrow, V-shaped valleys were eroded only slightly by the ice"; and again, "what seems to have happened, however, in Bakerville area, is that during the great part of the period the area, except possibly on the uplands, was actually protected from erosion by the ice-sheet which was nearly stagnant."[2]

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3. Many terraces are present. These have an irregular ice-contact face, showing no evidence of movement of the ice. They generally have a horizontal, level surface but small kettles are nearly always present. The terraces described by Flint show all of the foregoing characteristics, but he says that, in addition, spillways are present and that the foreset beds in the terraces face toward them. Unfortunately, when the observations were made in the Cranbrook district the possible occurrence of spillways was not considered and, if present, they were not recognized.

4. The streams occupying the large kettles wander aimlessly across the irregular bottoms and are too small to have excavated these depressions. In the terms of W. M. Davis they are "underfit."

5. Kames and eskers are distributed without apparent system over the entire floor of the trench. In normal retreat the distribution of these features is definitely related to the positions of the retreating glaciers.

The agreement of these observed features with the criteria summarized by Flint is so striking that it is believed to prove that the disappearance of the ice from the Cranbrook portion of the Rocky Mountain trench was by stagnation and dissipation instead of by normal retreat. This method of removal of the ice has been demonstrated in many places along the fringe of the Pleistocene ice sheet but never, so far as the writer is aware, in any part of British Columbia.

SUMMARY

The known glacial history of the Cranbrook district is briefly as follows:

1. The area was covered during Wisconsin time by the Cordilleran ice sheet, varying from a few hundreds of feet in thickness in the mountains to many thousands of feet in the valleys. The ice as a whole moved to the southeast over a land surface physiographically resembling the present one. Erosion was severe only among the high mountains; in the trench the ice overran unconsolidated material without disturbing it greatly.

2. As the ice melted from the ridges alpine glaciers came to occupy the valleys and set up independent glacial systems controlled by the local topography. During this stage there was little

glacial erosion in the lower stretches of the majority of the valleys or in the trench itself.

3. In the mountainous parts of the area the retreat of the glaciers was normal.

4. In the low-lying trench the ice stagnated and broke up into separate masses, many of large size, which gradually melted away.

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A CRITICISM OF THE GLACIAL-CONTROL THEORY

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ABSTRACT

A critical review of literature dealing with the glacial-control theory for the origin of coral reefs shows that Pleistocene low-level abrasion, one of the fundamental postulates of the original theory, has long been abandoned by Daly, the theory's chief advocate. Many others still retain this postulate of the original version, though serious objections have been brought against it. We question the efficiency of mud control and certain other features of Daly's revised versions of the theory. We believe that the theory offers a satisfactory explanation for the widespread occurrence of drowned valleys and that Pleistocene conditions stimulated reef growth, but do not believe that barrier reefs and atolls originated for the first time as a result of the peculiar conditions of glaciation. We support the antecedent-platform theory, which states that any bench or bank situated at a proper depth in the coral seas is a potential reef foundation and that, if ecological conditions permit, a reef can grow to the surface from such a platform without a change in ocean level.

INTRODUCTION

Owing chiefly to the writings of R. A. Daly, students of coral reefs have become very familiar with the ingenious "glacial-control theory." This theory has just as much appeal and is just as easily teachable as its older rival, the subsidence theory of Darwin and Dana. Both ideas are set forth in most textbooks, and both are considered in most courses in elementary geology. Each appears to have a following far larger than that of any other theory of reef origin.

Three extended field seasons among the coral islands of the Pacific have convinced us that, of the many reefs which we have studied, neither of the two leading theories offers a satisfactory explanation. We have recently discussed some of the difficulties of the subsidence theory.[1] Our present purpose is to point out what appear to be major defects in the glacial-control theory and to show that many writers have misunderstood the fundamental postulates of that theory. Daly's contributions to the problem of coral-reef origin have been at least as valuable as those of any other writer, and we firmly believe that continental glaciation affected reef growth and cannot be ignored by any theory of reef origin. We cannot, however, accept

[1] J. E. Hoffmeister and H. S. Ladd, "The Foundations of Atolls," *Jour. Geol.*, Vol. XLIII (1935), pp. 653–65.

Daly's conclusion that barrier reefs and atolls are structures resulting entirely from the peculiar conditions imposed upon the world by Pleistocene glaciation.

To give the proper background, it will be illuminating to follow the development of the theory by Daly. His first discussion appeared in 1910.[2] In this version Daly recognized three important elements, or "glacial controls," as they were later called. These, taken in the order in which they became operative, were: (1) a lowering of sea temperatures and sea level, which killed off reef corals over wide areas; (2) Pleistocene marine erosion, which operated efficiently at a lowered level on land areas and shoals; and (3) a raising of sea temperatures and sea level, which allowed reef corals to colonize the newly formed benches and shoals to form reefs.

LOW-LEVEL MARINE EROSION

In the first version a very important rôle was assigned to low-level marine erosion. It appears, indeed, to form the heart of the theory. Thus Daly says: "Most of the plateaus from which annular and barrier reefs rise are credited to Pleistocene marine erosion operating on Tertiary islands, shoals, or continental shores."[3] On page 303 of the same paper the plateaus are again credited essentially to Pleistocene marine abrasion. On the following page he slightly qualifies these rather definite and very sweeping statements. He says that a large proportion of the truncated volcanoes which served as atoll foundations were, in their subaërial portions, composed of massive lavas, as well as weaker ash and tuff deposits; and he confesses that to reduce such masses by wave erosion would demand vastly more time than is represented in the glacial period. He does not doubt, however, that the volcanoes which served as atoll bases were of many different ages and that the older ones had approached or reached peneplanation by subaërial erosion before Pleistocene time. He states that such denudation, combined with pre-Pleistocene

[2] R. A. Daly, "Pleistocene Glaciation and the Coral Reef Problem," *Amer. Jour. Sci.*, 4th ser., Vol. XXX (1910), pp. 297–308.

[3] *Ibid.*, p. 298.

marine erosion, had reduced most of the volcanic masses to plateau form. After these qualifications, he says:

> We may conclude that marine erosion, under Pleistocene conditions, was amply competent to reduce most of the Tertiary thalassic islands to a low Pleistocene sea-level. The same is true of the Australian continental shelf and that of the similar shelves of New Guinea, Fiji, etc.[4]

His final remark on this subject in his first paper is: ". . . . the development of the smooth floors, on which the existing reefs stand, is not to be ascribed to Tertiary marine erosion."[5]

In some of Daly's later expositions of the theory the effect of Pleistocene low-level marine erosion is regarded as unimportant, and its place taken by a new control, so that in his last work Daly refers to the "three chief Glacial controls—changing sea-level, oscillations of sea temperature, and induced turbidity of the shallower waters of the globe,"[6] and states that the last is not the least important. Before weighing the importance of the new control, it may be well to consider the consequences of abandoning the old one.

The postulate of extensive low-level erosion was certainly one of the most attractive features of the theory, but it seems also to have been its weakest feature. Four years after the appearance of Daly's original paper, W. M. Davis critically reviewed it, and cast doubts on the ability of low-level erosion to truncate large masses.[7] Daly, in his second paper,[8] which appeared in 1915, modified this postulate, saying:

> The offered explanation . . . . does not imply that any large proportion of the total erosion suffered by oceanic islands was accomplished during the Glacial period, but merely that the reef platforms were then finally smoothed by the removal of thin veneers of relatively weak materials formed on the ocean plateaus in Tertiary and pre-Tertiary times.

It seems to us that with low-level erosion thus made unimportant we have, in effect, merely returned to the theories of pre-existing

[4] *Ibid.*, p. 305. [5] *Ibid.*, pp. 307–8.

[6] *The Changing World of the Ice Age* (Yale University Press, 1934), p. 253.

[7] W. M. Davis, "The Home Study of Coral Reefs," *Amer. Geog. Soc. Bull. 46* (1914), pp. 730–31.

[8] R. A. Daly, "The Glacial-Control Theory of Coral Reefs," *Proc. Amer. Acad. Arts and Sci.*, Vol. LI (1915), pp. 159–60.

platforms advanced by Tyerman and Bennet, Wharton, Agassiz, Andrews, Vaughan, and others. As will be shown later, Daly himself does, on occasion, recognize a relationship to the above mentioned theories. Chamberlin, in 1924, reviewed the glacial-control theory carefully and remarked that by the shift in emphasis in regard to Pleistocene abrasion the theory seemed to lose one of its chief reasons for being.[9]

Daly's first paper (1910) is the one in which he makes the strongest case for Pleistocene low-level erosion. It may seem somewhat unfair to resurrect a preliminary version of a theory, but in this case it appears justifiable in the light of the following discussion. This first version was widely read; and apparently it made a decided impression, for many of those who write about coral reefs still cling stubbornly to the original form of the theory, and none of Daly's later writings, nor the paper by Chamberlin cited above, have succeeded in removing the idea of Pleistocene low-level erosion as a cornerstone of the glacial-control theory. The concept got into the textbooks, and in some of the newer ones it still occupies a most prominent position. This is not so surprising as the fact that many writers of special articles dealing with the origin of certain coral reefs have failed to recognize that Daly himself, on several occasions during the past twenty years, has denied any real importance to low-level erosion.

We believe, however, that Daly himself is partly responsible for this state of affairs because of certain inconsistencies in some of his papers. It has been shown that in his second paper (1915) he met the criticism that greeted his first effort (1910) by categorically denying the importance of low-level erosion. Yet, in this same paper appear statements which—by implication at least—show that he had by no means abandoned his faith in this process. For example, in his "General Conclusion" he says:

> The new theory really supports the conclusions of Tyerman and Bennet (1832), Wharton, Agassiz, and others, who have seen, in whole archipelagoes, the independence of reef and reef platform. A weakness in their arguments has been the failure to show a good reason why protecting reefs were absent from

[9] R. T. Chamberlin, "The Geological Interpretation of the Coral Reefs of Tutuila, American Samoa," *Carnegie Inst. Wash. Publ. 340* (1924), pp. 170–76.

most inter-tropical shores for a total time long enough for the marine abrasion assumed. A second important ground for scepticism regarding their views is the depth of water on the platforms, measuring so commonly 50 m. to 90 m. or more. The time necessary for the sea to cut benches so far below its surface must be so greatly extended that one's faith in the thesis is handicapped. The difficulty is the more portentous because the older statement of the abrasion hypothesis expressly or tacitly assumed the abrasion to have occurred when the sea had its present level, and also that the earth's crust, throughout nearly all of each coral-reef region, remained essentially stable during the immense time implied in the cutting of very wide benches at depths of from 50 to 90 m. *Neither of these difficulties exists for the Glacial-control theory.*[10]

How does the glacial-control theory avoid these difficulties unless Pleistocene low-level abrasion did more than merely "smooth" platforms that existed in preglacial times? Other passages in the same paper seem to show even more clearly that, although, on page 159, Pleistocene erosion was denied an important rôle, yet, on later pages, it is called upon to function very efficiently. Thus, on page 183, in speaking of the Pleistocene, Daly says: ". . . . a fair judgment seems to indicate that composite benches, of area and depth corresponding to the platforms from which the present coral reefs rise, *were then actually cut in islands and coastal plains.*"[11] Later he says: ". . . . the present reefs are shallow veneers on benches formed by Pleistocene waves at levels averaging about 70 m. below present sea-level."[12] It seems certain that a considerable amount of confusion has been caused by such mobility in the theory.

In Daly's third paper the rôle of low-level abrasion is so emphasized that it nearly reaches its original importance, as is shown by the following quotation:

When it is remembered that oceanic islands and shoals are subject to wave action on all sides, there is no difficulty in believing that many of the less resistant structures, *twenty miles or more in diameter*, might be completely truncated and smoothed by the waves, during merely the time of maximum glaciation. Just as clearly the waves could make little impression on hard lavas, so that young volcanic islands should today have but narrow submarine benches. Narrow or broad, the wave-formed facets would generally be from thirty to

[10] "The Glacial-Control Theory of Coral Reefs," *loc. cit.*, pp. 248–49. The italics are ours.

[11] The italics are ours.

[12] "The Glacial-Control Theory of Coral Reefs," *loc. cit.*, p. 209.

ninety feet below the sea-level of the Glacial period and from 200 to 300 feet below the present sea-level. According to the Glacial-control theory, it was on these platforms that the existing living reefs have grown.[13]

In 1919, Daly published another paper,[14] which was intended as a supplement to his detailed discussion in 1915 and to clear up some misunderstandings of his earlier views. On page 140 of this publication he states that at the beginning of the glacial period there existed in the sea many banks of varied history. On page 146 he qualifies an earlier statement as to the continuity of Pleistocene abrasion by stressing the likelihood of vigorous reef growth during one or more of the interglacial stages. The growth of such reefs would reduce the effectiveness of low-level abrasion; and Daly believes, therefore, that he had somewhat overstated the case for continuous Pleistocene abrasion. The relative unimportance he now ascribes to this control is clearly brought out by the following on page 150: ". . . . Pleistocene wave abrasion merely 'sand-papered' structures of which the heavy sculpturing or accretional formation had been accomplished long before." In the summary on page 158 of the same paper appears the following:

> A specially notable effect of the lowering of sea-level during glaciation is seen to have been the shallowing of water on the banks and shelves then existing, so that corals could take root on the edges of these submarine plateaus. In comparison, the platforms due primarily to Pleistocene abrasion are less important.

In papers published in 1924,[15] 1925,[16] 1929,[17] and 1934,[18] low-level abrasion continues to occupy an unimportant position. In fact, in the 1929 paper, in explaining the rarity of cliffs along the shore of the ocean, Daly cites as the leading reason the brevity of Pleistocene low-level abrasion.

[13] "Problems of the Pacific Islands," *Amer. Jour. Sci.*, 4th Ser., Vol. XLI (1916), p. 176. The italics are ours.

[14] "The Coral-Reef Zone during and after the Glacial Period," *Amer. Jour. Sci.*, 4th ser., Vol. XLVIII (1919), pp. 140, 146, 150, 158.

[15] "The Geology of American Samoa," *Carnegie Inst. Wash. Publ. 340* (1924), pp. 126–27.

[16] "Pleistocene Changes of Level," *Amer. Jour. Sci.*, 5th ser., Vol. X (1925), pp. 289–392.

[17] "Swinging Sealevel of the Ice Age," *Geol. Soc. Amer. Bull. 40* (1929), p. 733.

[18] *The Changing World of the Ice Age*, pp. 247–48.

MUD CONTROL

The factor of mud control was first introduced by Daly in 1915. In his later papers it has come to occupy an increasingly important position. Daly believes that the deposits which covered the pre-Pleistocene banks contained a high percentage of mud. He says:

> When, with the onset of the first glaciation, the sea level fell by about 100 meters, the waves breaking on all the coasts of the world . . . . stirred up immense quantities of mud and sand that had been deposited during the previous period. Fringing reefs could not thrive in such muddy asphyxiating baths, nor could their corals effectively colonize the shelves farther out to sea. Only in sheltered places, where storms did not so vigorously stir the bottom muds, could the corals be happy.[19]

This muddiness, coupled with lowered temperature, is thought to have been sufficient to kill off reef corals over much of the tropical world at the beginning of each glacial stage.

During each glacial stage the waves of the lowered sea level are said to have winnowed out the finer sediments; these were carried out to deep water, never to return to the shallows. As a result coarse sands and shelly material became concentrated on the surface of the shelves and banks; and when the ice caps began to melt and the sea level to rise, the waters were cleaner than previously and more suitable for coral growth. Beach rock is thought to have been widely formed and to have served as a firm foundation on which the corals could establish themselves. Beach rock is lithified sand or coarser débris. It is being formed today between the tide marks along many shores in the tropics.

Daly is firmly convinced that this mud control is a factor of the greatest importance. He uses it in explaining the location of reefs on the peripheries of their platforms, in explaining the growth of small patches of reef in lagoons, and in explaining the more advanced development of atoll reefs on their windward side. He believes that muds, stirred up by occasional hurricanes, have killed off corals locally in great numbers and that in this manner certain "drowned" reefs may be explained. Mud control is still an important factor today, Daly believes, and may well be responsible for the reefless or reef-poor condition of about half of the intertropical shores of the

[19] *The Changing World of the Ice Age*, pp. 238–39.

Indo-Pacific region.[20] During the Pleistocene, according to him, it may have been a more important factor than the lowering of sea temperatures.[21]

All students of corals and coral reefs will concede that muddy waters make any environment less suitable for coral growth and that large deposits of mud will, if not removed, kill corals and put at least a temporary end to reef growth. Mud control today and in the past is a factor to be seriously considered, but our observations on modern reefs lead us to conclude that Daly has greatly overemphasized the importance of such control.

Observations such as those made by Mayor in Samoa[22] indicate that when fresh waters laden with silt pour over a reef the corals suffer greatly. However, it is not possible to say how much of the damage in such a case was due to the freshening of the water and how much to the presence of the silt. The experiments of Edmondson[23] have a more direct bearing on the question under discussion. He buried corals under 4 inches of sand and silt but kept a strong current of sea water circulating over them. Of the twenty-three species of Hawaiian corals thus treated, all but two survived a burial of 12 hours. At the end of 5 days, usually all but three were dead; but some individuals survived a burial of 10 days. These experiments show that corals vary greatly in their ability to withstand burial, and it seems that some are remarkably hardy.

A distinction must be made, of course, between the ability of corals to withstand burial and their ability to withstand a mere muddying of the water. Prolonged burial will kill any coral; but the main feature of mud control, as described by Daly, seems to be an increase in the turbidity of the waters. In his last discussion he speaks of muddy, asphyxiating baths, of a stirring of the bottom muds, and of a world-wide increase in the turbidity of the waters. Local areas undoubtedly would be buried temporarily as the waves

[20] "Pleistocene Changes of Level," *loc. cit.*, p. 290.

[21] "The Coral-Reef Zone during and after the Glacial Period," *loc. cit.*, p. 158.

[22] A. G. Mayor, "Structure and Ecology of Samoan Reefs," *Carnegie Inst. Wash. Publ. 340* (1924), p. 24.

[23] C. H. Edmondson, "The Ecology of an Hawaiian Coral Reef," *Bernice P. Bishop Mus. Bull. 45* (1928), pp. 49–51, 61–62.

re-worked the deposits of new levels made accessible by the lowering sea level; but, according to Daly, these fine sediments were on their way to deeper waters and in their passage they made the waters turbid. We must consider, then, the effect of increased turbidity. Its most important effect would be to decrease the depth to which light could penetrate, and this would have its greatest effect on corals living on the deeper portions of a submerged foundation. As regards the colonies living in shallow water, this effect would not be so important. Many types of corals do not thrive in muddy waters; but others, such as certain species of *Porites*, a most important genus of reef-building corals, grow abundantly in such waters. The waters covering the reef flats at points near the mouth of the Mba River on the island of Vitilevu, Fiji, are heavily laden with silt at certain times—we have seen them so murky that visibility of the bottom was limited to about 3 feet—yet colonies of *Porites* cover a large proportion of the reef surface. On the opposite side of Vitilevu, reefs are present in spite of the tremendous amounts of silt brought to the sea by the Rewa River.

Mayor states that when he first saw the barrier reef off the entrance of Suva harbor in 1898 it was remarkably rich in corals, but that 20 years later the reef was largely killed by mud from the harbor and from the nearby Rewa River delta, and that two years later it had suffered even more, apparently by sewage from the growing town of Suva.[24] When we first examined these reefs in 1926, we found a flourishing growth of corals along their seaward border and extensive areas of living corals on the reef flats themselves. We also examined them in 1928 and again in 1934 but noted no changes worthy of mention. The remarkable feature is not that such a reef receives a setback such as Mayor describes but that corals can continue any sort of growth so close to a river like the Rewa. This river, probably the largest in the islands of the open Pacific, drains an area of soft marls and claystones which were uplifted at the close of the Miocene. It has been pouring its silts into the ocean for a long time and has not yet succeeded in killing the corals in the immediate vicinity of its delta.

[24] Mayor, *op. cit.*, p. 25.

COLONIZATION BY CORALS

"After each glacial stage," according to Daly, "the coral larvae could issue from warm, sheltered inlets of the sea and with relative speed colonize the appropriate shallows."[25] Even if one should concede that the corals were largely killed off during each glacial stage, one may, perhaps, question the relative speed with which they could migrate from the restricted localities in which they survived to the regions which were so slowly being prepared for their occupancy. Particularly would this be true of those platforms located in the marginal belts of what are now the tropical areas. Even at the present time, coral genera which are widely established in the equatorial portions of the coral seas are not found in the marginal belts. One of the best examples is the genus *Acropora*,[26] which, though a most important reef-builder in the South Seas and the West Indies, has never reached Hawaii nor Bermuda. Likewise, as Vaughan has shown,[27] Hawaii lacks species of such important families as the Mussidae, the large, massive, meandroid Faviidae, the Oculinidae, Eusmiliidae, and Astrangiidae. Even specimens belonging to the important family Orbicellidae are very rare. Dana explained this by pointing out that the Hawaiian Islands lie outside the torrid zone of oceanic temperature and that consequently there are fewer species of corals and a less luxuriant growth.[28] Vaughan, however, believes that probably the larvae of some genera cannot be transported long distances, and he believes that in this lies the true explanation. His contention is supported by the recent work of Yabe and Sugiyama on the reef corals of Japan.[29] Probably both of these factors play important parts in the problem. It is reasonable to suppose that platforms far removed from centers of dispersal could not be colonized until conditions governing the hazardous larval migration were exactly right. In view of the fact that in certain localities these con-

[25] "Swinging Sealevel of the Ice Age," *loc. cit.*, pp. 729–30.

[26] One species of *Acropora*, represented by one specimen, is doubtfully reported by Vaughan from Hawaii, *U.S. Natl. Mus. Bull. 59* (1907), pp. 48, 158.

[27] T. W. Vaughan, "Recent Madreporaria of the Hawaiian Islands and Laysan," *U.S. Natl. Mus. Bull. 59* (1907), p. 48.

[28] J. D. Dana, *Corals and Coral Islands* (3d ed.; Dodd, Mead and Co., 1890), p. 111.

[29] H. Yabe and T. Sugiyama, "Geological and Geographical Distribution of Reef Corals in Japan," *Jour. Pal.*, Vol. IX, No. 3 (1935), p. 213.

ditions are still not right, we are led to conclude that corals could not become established on many platforms, particularly on those in the marginal zones, until the waning of the ice sheets had progressed to a considerable extent. Sea level must have risen appreciably before many of the coral reefs were well established.

PRE-PLEISTOCENE CORAL REEFS

Let us now consider the coral reefs of preglacial times. From the start Daly has maintained that barrier reefs and atolls, with the possible exception of a few small ones formed by subsidence, probably did not exist before the Pleistocene. In his first paper, however, he emphasizes the importance of preglacial fringing reefs, stating that they doubtless flourished in equatorial seas during the Tertiary period and thus greatly protected the islands and mainlands from wave attack.[30] In this same paper he voices the opinion that the total area of many of the Tertiary coral reefs was much greater than that of existing coral reefs.[31] These statements were made at a time when Daly believed in the effectiveness of low-level Pleistocene wave abrasion in cutting wide platforms. In order to show the inadequacy of pre-Pleistocene marine erosion as an agent in platform-cutting, Tertiary reefs were considered flourishing, wave-resisting structures. Later, when low-level abrasion was abandoned as an important agent, preglacial marine erosion was called upon to explain the wide platforms. This made it necessary to reconsider the effectiveness of the Tertiary reefs as protectors of the land.

In doing this, Daly points out that a reef's ability to resist abrasion depends upon a kind of co-operation among the reef species. As he believes that this co-operation did not exist before late Tertiary times, he concludes that in earlier times reefs were not effective wave-resisters, and that islands were subject to complete truncation by waves during a number of geological periods.[32]

He then cast doubt on the continuity of reef growth in preglacial times, stating that during a part of the Tertiary the intertropical area may have been too hot for vigorous coral growth.[33]

[30] "Pleistocene Glaciation and the Coral Reef Problem," *loc. cit.*, p. 307.

[31] *Ibid.*, p. 304.

[32] "Problems of the Pacific Islands," *loc. cit.*, p. 183.

[33] *Ibid.*, p. 183.

His latest belief, and the one in which he would now doubtless place most reliance, is that the seas of preglacial times were probably too muddy to have supported a thriving coral fauna. He believes that the waves of lowered Pleistocene sea level cleared the shallow seas of mud and that, prior to this clearing, fringing reefs could not thrive as they do now.[34] Yet, as late as 1929, long after he had begun to doubt the effectiveness of preglacial reefs as wave-resisters, he conveniently used the preglacial fringing reefs to explain the absence of the cliffs which Davis believed should exist behind reefs if they rested on platforms of abrasion.[35]

It is well known that reef corals flourished in Tertiary times. Most of the genera found in the seas today are plentiful in the Tertiary rocks, as are many of the common species. Likewise, in close association with the corals in Tertiary rocks are the remains of other organisms which are found on coral reefs today. Particularly plentiful are the encrusting algae which play such an important part in binding the coral heads together. Some of these are identical with species living in the Pacific today. We have found many of them in the Tertiary of Fiji and Tonga. All the reef-building organisms flourished in the Pacific during Miocene and Pliocene time, and there is no reason to believe that they did not build reefs capable of protecting the land.

We fully realize the hazards of applying the name "coral reef" to every limestone that contains corals. We are also well aware of the fact that a great many elevated coralliferous limestones have been erroneously termed coral reefs by various writers. Therefore, we limit our examples of elevated Tertiary coral reefs to those which we ourselves have seen, although undoubtedly many of those reported as such are actually true reefs.

On one side of the island of Eua in the Tongan group is an excellent example of an elevated barrier reef of Pliocene age; on the opposite side of the same island there is an elevated fringing reef of the same age. Most of the coral heads in these reefs are in positions of growth and are held together by the cementing algae. Furthermore,

[34] *The Changing World of the Ice Age*, pp. 236–37.

[35] "Swinging Sealevel of the Ice Age," *loc. cit.*, p. 733.

the barrier was built on a pre-existing platform during stages of still-stand and uplift, and not during subsidence of the island.[36]

We observed elevated coral reefs in a number of islands in Lau (eastern Fiji), and studies now in progress indicate that most of these date from the Tertiary. Miocene limestones showing many coral heads in positions of growth were also studied near Suva on Vitilevu.[37] Thus it may be concluded that coral reefs similar to those of the present day existed during Tertiary times.

PLEISTOCENE CORAL REEFS

In his first statement of the theory—the one in which low-level abrasion plays an important part—Daly makes no reference to the possibility of reefs developing in the interglacial stages; but in the fuller statement of 1915 he expresses the opinion that the interglacial stages ". . . . may have witnessed a partial re-establishment of reefs in the open ocean, but, if so, such reefs must have been relatively feeble and short-lived defenders of the islands."[38] In the 1919 version he lays more stress on the likelihood of vigorous reef growth during one or more of the interglacial stages and assumes the development of barriers, atolls, and fringing reefs.[39] In the 1925 paper it is explained that the reefs formed during the first interglacial stage were more or less completely cut away by the waves during the second glacial stage, and that after the final planation the living reefs of today developed.[40] Similar statements appear in his latest account;[41] but it is explained that in a few places, such as the Banda Sea area, the great width of reefs suggests that growth was not interrupted during the Pleistocene.[42]

IMPORTANCE OF RISING WATERS

Daly has ignored published descriptions of elevated Tertiary barrier reefs and atolls and has concluded that, since there is no evidence

[36] J. E. Hoffmeister, "Geology of Eua, Tonga," *Bernice P. Bishop Mus. Bull. 96* (1932).

[37] H. S. Ladd, "Geology of Vitilevu, Fiji," *Bernice P. Bishop Mus. Bull. 119* (1934).

[38] "The Glacial-Control Theory of Coral Reefs," *loc. cit.*, p. 180.

[39] "The Coral-Reef Zone during and after the Glacial Period," *loc. cit.*, p. 146.

[40] "Pleistocene Changes of Level," *loc. cit.*, p. 291.

[41] *The Changing World of the Ice Age*, pp. 240–41.

[42] *Ibid.*, p. 255.

of such, we are not justified in assuming their abundance in preglacial times. From this position he surveys the Pleistocene, seeking, in the peculiar conditions of those days, some explanation for the sudden appearance of large numbers of both types of reef. He finds several special conditions which he regards as favorable, or essential, to the growth of such reefs. One of these is the rise of sea level that succeeded each stage of glaciation.

He believes that "in order to explain the heights of the living reefs, heights which commonly reach 75 or more meters, a rise of sea-level on the foundations must be postulated."[43] It is logical to assume that the shallowing of waters due to the lowering of sea level might allow corals to colonize banks and shoals inaccessible at normal sea level, but we do not believe that many coral reefs extend to depths greater than those at which corals can live. Before concluding that the rising preglacial waters are an important factor in explaining modern reefs, two questions must be considered: (1) What is the greatest depth at which reef corals can live (their "depth limit")? (2) How thick are modern reefs?

The depth limit of reef corals, particularly the greatest depth at which they can grow in sufficient numbers to produce a reef, is variable, because it depends upon the clearness of the water and other variable factors. It seems to us that Daly is very conservative in the depth limits which he assigns for reef growth. In 1916, citing Gardiner as his authority, he set the limit at 120 feet.[44] In his latest statement (1934) he is even more conservative, stating that for vigorous growth reef-building corals require a location not greater than 20–30 meters below the surface of the sea.[45] Gardiner in a volume published in 1931 mentions this matter several times. On page 63 he states that no reef corals in a fixed and growing condition have been discovered at greater depths than about 40 fathoms. On the following page he gives the results of dredgings by the "Sealark" in the Indian Ocean, which show that, though a fair number of reef

[43] "Swinging Sealevel of the Ice Age," *loc. cit.*, p. 731.

[44] "Problems of the Pacific Islands," *loc. cit.*, pp. 178, 184.

[45] *The Changing World of the Ice Age*, p. 213.

corals were obtained at depths between 36 and 40 fathoms, only one was obtained in 23 dredgings in waters between 41 and 50 fathoms. Gardiner concludes with the following:

> If we summarize all field observations, we are driven to conclude that the maximum depth from which reef corals could commence to form a reef is approximately 50 fathoms, while a suitable environment in such a depth for the growth of corals to form a reef can only be found on the banks in the clearest waters of the open ocean, which actually are situated nearest to the equator and in the western halves of the Indian and Pacific Oceans.[46]

Even if the figure of 300 feet set by Gardiner is the limit attained only under ideal conditions, the figure of 98 feet set by Daly seems too conservative. We believe that, if a definite figure must be selected, 200 feet (about 60 meters) would be more nearly correct than either 120 or 98 feet given by Daly. Perhaps there would not be many places where reef corals would *flourish* at this depth, but many colonies could grow and, with the aid of other organisms, particularly calcareous algae,[47] build up a foundation to a depth where the corals *could* flourish. The mean depths of very few lagoons exceed this figure, and we therefore believe that very few reefs have a thickness exceeding it. Our studies of elevated reefs support this contention.

We believe that the shifting sea level of Pleistocene times may have aided reef development in two ways: (1) the lowered sea level made accessible for colonization certain banks which had been too deeply submerged for coral growth during earlier times; and (2) the rising waters stimulated reef growth. Reef corals can grow at depths of 200 feet, but they grow in greatest profusion in shallower waters where light is strong and other factors are more favorable. Therefore reefs would grow more rapidly beneath a shallow cover of gradually deepening water than beneath 200 feet of water, the surface level of which remained unchanged. However, we do not believe that a rising sea level is essential to the formation of either barriers or atolls. Given a suitable foundation, either type of reef may be formed under stable conditions of depth by normal upward growth.

[46] J. S. Gardiner, *Coral Reefs and Atolls* (Macmillan & Co., 1931), pp. 63–64.

[47] For a discussion of the importance of algae as reef-builders at considerable depths see W. A. Setchell, "Phytogeographical Notes on Tahiti," *Univ. Calif. Publ. in Botany*, Vol. XII (1926), pp. 312–17.

DROWNED VALLEYS AND GLACIAL CONTROL

One of the most important contributions made by the glacial-control theory is the alternative explanation which it offers for many embayed coasts. The widespread occurrence of such coasts in the coral seas was a most important support for the venerable subsidence theory. Glacial control offers a much more satisfactory explanation for these features than does subsidence of the type postulated by Darwin and Dana. Few will doubt that ocean level was appreciably lowered during the glacial stages and that the valleys then existent were deepened and widened. Rising waters at the close of the Pleistocene would convert the enlarged valleys into embayments. Arguments brought against the glacial-control theory as it affects coral reefs do nothing to invalidate this explanation of drowned valleys.

Furthermore, we agree that in minor ways Pleistocene erosion and deposition aided in forming foundations for coral reefs. Both processes doubtless served to widen existing platforms and, perhaps, to initiate new ones. Benches and banks existed in pre-Pleistocene time, and undoubtedly barriers and atolls did also.

THE ANTECEDENT PLATFORM THEORY

The first requisite for any coral reef is a suitable foundation upon which it may become established and grow. According to the subsidence theory, this foundation is, in most cases, an island whose sloping sides can support a fringing reef. As the island slowly subsides, the fringing reef grows into a barrier and eventually into an atoll. In this way the contact between the reef and the underlying foundation is an unconformable one. The glacial-control theory requires "smoothed" pre-existing platforms for its barriers and atolls. These platforms were made in preglacial times and smoothed during stages of maximum glaciation and lowered sea level. On them reefs developed with rising sea level during each of the interglacial stages and during the time which has elapsed since the last glaciation.

Our experience in coral-reef areas has caused us to doubt the validity of the two above mentioned theories and to support the antecedent-platform theory. This theory holds that any bench or bank—even one not "smooth"—that is located at a proper depth within the circum-equatorial coral reef zone can be considered a po-

tential reef foundation, and that, if ecological conditions permit, a reef could grow up to the surface without any progressive change in ocean level. This is a general principle that applies to all reefs—preglacial, glacial, and postglacial.

The theory is not new. The first coral-reef theory that postulated a pre-existing platform appeared more than one hundred years ago. Davis, in his voluminous work on *The Coral Reef Problem*,[48] has reviewed all of the important platform theories. Many writers on the subject have been inclined to stress one particular method of platform-building, but Vaughan has shown clearly that many types of platforms have served as reef foundations.[49] Chamberlin, likewise, in discussing the reefs of Tutuila, states that they have developed on antecedent platforms ". . . . wherever and whenever the conditions were favorable."[50]

In requiring a pre-existing platform, the theory which we support resembles the glacial-control theory. It holds that the special conditions of the Pleistocene probably stimulated reef growth, but it does not concede that these conditions are essential to the development of barriers and atolls. Obviously, one of the main differences between the two theories is that one requires a steadily rising sea level for reef development; the other maintains that no change in level is necessary, normal growth enabling the reefs to reach the surface of the sea. Only by implication does Daly recognize the ability of a reef to establish itself and grow upward after its platform is covered with water to an appreciable depth. He states that, following glaciation, "in most cases the corals began vigorous growth on the platforms, before the covering water reached the depth of about 120 feet below which the corals cannot thrive."[51] This can only be taken to mean

[48] W. M. Davis, *The Coral Reef Problem*, "Amer. Geog. Soc. Special Publications," No. 9 (1928).

[49] T. W. Vaughan, "Corals and the Formation of Coral Reefs," *Ann. Rept. Smithsonian Inst. for 1917* (1919), p. 235.

[50] R. T. Chamberlin, "The Geological Interpretation of the Coral Reefs of Tutuila, American Samoa," *Carnegie Inst. Wash. Publ. 340* (1924), pp. 177–78. In commenting on his paper in a recent letter, Chamberlin points out that benches of erosion and deposition were specifically mentioned because these are undoubtedly the most important, but that any other sort of foundation would serve under the specified "favorable conditions."

[51] "Problems of the Pacific Islands," *loc. cit.*, p. 178.

that he believes that, if the water were deeper than the 120-foot limit, reefs could not be produced but that, if the platforms were 120 feet or less in depth, reefs could grow up to sea level (this in spite of deepening water). It inevitably follows that if reefs could grow upward from platforms which were as much as 120 feet below sea level following glaciation they must also be able to do it today. Also, on suitable foundations they could have done it in pre-Pleistocene times.

In this connection should be mentioned the rimmed shelves and banks which exist at varying depths below sea level in some areas. These submerged reefs are referred to as "drowned" by the advocates of the subsidence theory. Daly believes that a few of the banks may have been drowned by actual down-warping of the reef foundations, but he thinks that most of them represent platforms on which reef growth may have been interrupted while general sea level was rising. This, he believes, will explain some barriers and atolls now covered by 5–30 meters of water. He states that hurricanes periodically stir up muds of adjacent shallows in amounts sufficient to inhibit the growth of corals and that such reefs are kept beheaded by the waves. He says that it would be difficult to distinguish such reefs from others that had grown up in an early interglacial stage and had become truncated during a later, reefless stage, but concludes that "whether of one or the other origin, the 'drowned' reefs add their testimony to the validity of the Glacial-control theory."[52] Such explanations may account for some submerged reefs, but is it not more plausible to consider most of these rimmed banks as incipient reefs which started their growth at a later date, or which are growing more slowly than reefs now at the surface? Setchell calls such reefs "barrier banks."[53] He looks upon them as living reefs that may eventually reach the surface.

In referring to reef foundations, we have used the word "platform" in a broad sense to include all foundations that have proved suitable for reef growth. We believe that the foundations beneath almost all of the modern reefs were fairly flat before the reefs became established on them and that they are properly to be described

[52] *The Changing World of the Ice Age*, pp. 241–44. [53] *Op cit.*, pp. 314–15.

as platforms. The smoothness of existing lagoon floors lends some support to this belief.

It is not the purpose of the present paper to detail the various methods of platform formation or to give examples of the various types. There are a limited number of general processes—erosion, deposition, volcanic eruption, and earth movements—but they vary in the importance of their rôles, and the combinations are endless. Each reef, living or elevated, must be studied in relation to its immediate surroundings. If a given reef foundation lies near a land mass, we may be able to evaluate the rôle played by each process; but in the case of large, open-sea banks it is, perhaps, a question whether or not we shall ever acquire sufficient information to ascertain their origin with confidence.

In conclusion we wish to say again that we recognize Pleistocene glaciation as an important factor to be considered by any theory seeking to explain the coral reefs of the present day. Daly, in developing this phase of the coral-reef problem has made a major contribution. We believe, however, that glacial control is only a factor. The favorable conditions created by widespread glaciation did not create barriers and atolls for the first time; they accelerated processes of normal growth that long antedate the Pleistocene. In the near future we intend to publish a more comprehensive account of the antecedent-platform theory which will be based largely on our field studies in Fiji and Tonga.

STUDIES FOR STUDENTS

GLACIER MOVEMENT AS TYPICAL ROCK DEFORMATION

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ABSTRACT

There is a close parallelism between the behavior of ice in a glacier and the behavior of rocks under stress in the earth. The resulting structures have much in common. Glacier movement is but rock deformation in progress. Solid-rock flow and the displacement of large masses of ice by shearing both take place in the same part of a glacier and are not mutually exclusive. The concept of a zone of fracture and a zone of flow, whether in the earth or in a glacier, is thought to be more harmful than helpful.

INTRODUCTION

Eight years ago the similarity between many of the structures observed in glacier ice and the familiar structures of deformed sedimentary and metamorphic rocks was discussed before the National Academy of Sciences at its Urbana meeting,[1] but the full paper was not submitted for publication. Five years ago some infelicities of our current concept of zones of fracture and flow in the outer part of the lithosphere were presented at the Toronto meeting of the Geological Society of America,[2] but again only an abstract appeared in print. Such abstracts are necessarily very inadequate and are also easily overlooked. More recently it has become apparent that the writer's views on the nature of glacier motion have been considerably misunderstood.[3] Though these topics at first may appear quite different in their scope and bearing, the processes involved and the questions pertaining thereto are in reality intimately related. Perhaps, therefore, a brief rehandling of these related subjects may not be amiss.

[1] R. T. Chamberlin, "Glacier Motion as a Type of Rock Deformation," *Science*, Vol. LXVI (1927), abst., p. 461.

[2] R. T. Chamberlin, "The Zone of Cavities and the Zone of Continuity," *Geol. Soc. Amer. Bull. 42* (1931), pp. 194–95.

[3] O. D. von Engeln, "The Motion of Glaciers," *Science*, Vol. LXXX (1934), pp. 401–3; Vol. LXXXI (1935), pp. 459–61.

GLACIER STRUCTURES

Snow falling on lofty alpine mountains, or on icecaps in polar regions, develops a rough layering or stratification due to surface melting and to the accumulation of dust between successive heavy snowfalls. The material of the surficial portion of the snowfield is therefore essentially a stratified sedimentary rock, poorly indurated. Buried under successive layers of fresh snow the older snow becomes compacted, and the original flakes gradually pass into granules by partial liquefaction and freezing and by a slower transfer of molecules in a general consolidating process which transforms the snow into ice. An indurated stratified rock results. With the passage of time various granules grow at the expense of others and more coarsely granular ice develops. The change parallels, to some extent, the passage of fine-grained limestone into coarse-grained crystalline limestone, or marble—a metamorphic rock.

Under the force of gravity the ice moves down the slope, where conditions permit, and becomes true glacier ice. Differences in movement, from changes in gradient and varying resistance, set up local tensile stresses which crack the brittle ice, and the cracks by widening and by melting of the walls become crevasses. These tension cracks bear close relation to the tension joints of other rock formations, though the dominance of glacier movement in one direction causes a special crack orientation of its own. This orientation varies in different parts of a glacier in response to systematically changing directions of tension and gives the general crevasse pattern so familiar to alpinists.

In the portions of the glacier where the ice has already moved for considerable distances, particularly in the lower ice tongue, a distinct cleavage and banding are manifest. These portions of the glacier are of metamorphic rock. The strike of these structures closely parallels the margin of the ice tongue and the dip is inward toward the middle of the moving mass. Along the side of a long ice tongue the banding stands at a high angle, as a rule, and in places becomes vertical, but near the terminus it is inclined at considerably less than 45°. So regular is the development that in case of fog one can find his way readily over large glaciers, locating himself approximately and steering his course, by noticing the strike and dip of the secondary plicated

structure. As the cleavage is due to shearing, whereas the crevassing results from tension, the crevasses cut across the cleavage and banding at the appropriate angles required by the relatively simple stress conditions.

The cleavage consists of a large number of shear planes along each of which the ice above has moved forward and upward over that below. The movement is simplest near the snout of the glacier. Here the push is mostly down the valley; there is no valley wall in front to offer resistance; the external resistance comes mainly from the bottom of the glacier, and the upper ice rides forward along shearing planes inclined at relatively low angles. Along the sides of a long glacier confined between valley sides there is some movement toward the margins to replace wastage, but there is a stronger component of movement down the valley parallel to the confining walls. Consequently the shear planes here parallel the glacier margins in strike but are very steeply inclined or even vertical.

Some of the shear planes are visible only as fractures and surfaces of slippage; others are made more apparent by slight accumulations of fine débris along them. Along some the movement has doubtless been slight, but along others it has obviously been very pronounced. A striking case of strong movement was observed on the Valdez glacier in Alaska in 1919. On its upper surface, though not more than a hundred yards from its right margin, the trace of an outcropping shear plane was marked by a line of well-rounded, water-worn pebbles which must have been dragged upward from a subglacial stream bed by movement along this shearing plane.

Paralleling the fracture cleavage, except where more than one episode of deformation under differently oriented stresses is apparent, is a banding which consists of layers of whitish ice containing numerous small air bubbles and other layers of bluish ice relatively free from bubbles. The blue bands are thinner than the white bands and seem to represent old shearing planes along which water has subsequently frozen and from which the air bubbles have been largely expelled.

The blue bands are particularly useful as recorders of deformation and as indices of more than one episode of deformation. In various places they have been offset by thrust faults cutting them at acute angles. In some cases the faults are recent shear planes still in the

crack stage; in other cases blue bands of an older set have been offset by younger blue bands which represent fault planes subsequently healed. Both types indicate an earlier system of fracturing and shearing followed later, when the direction of the shearing stresses had changed appreciably, by a differently oriented system of younger faults. One is reminded of the offset veins often seen in strongly deformed crystalline rocks.

Not only are blue bands faulted, but in certain places they have undergone notable folding. Striking overturned and even recumbent folds have formed under favorable conditions of differential movement. Particularly conspicuous are cases in which zones of débris insinuated along earlier lines of slippage have been contorted during later bending and folding movements. Photographs of such folds have been reproduced extensively in the literature on glaciers.

In summation, the chief structures noted in deformed rocks are observed also in glaciers. It is natural that they should be. As glacier ice is a true rock, it should behave, under deforming stresses, according to the same mechanical principles as other rocks. Though different rocks have different properties, and glacier ice has its own peculiarities, they all have much in common. The movements and deformation of glacier ice should be interpreted in the light of what we know about rock deformation in general.

PROCESSES OF MOVEMENT AND DEFORMATION

The principal phenomenon of glacier activity is the transfer of ice in large volume from the region of alimentation to the region of wastage. Snow accumulates in layered snowfields and ends as coarsely granular, crystalline ice. That is the fundamental change occurring during the glacier journey. Incidental, though very significant, are fracturing in crevasses, shearing and the development of cleavage, thrust faulting, and folding. The ice mass in its journey down a winding valley is molded to the irregularities of the way, the middle of the glacier moving faster than the sides, and the upper portion more rapidly than the basal part. Debouching onto a plain beyond the mouth of a valley, it spreads out fan-like.

The basic process.—Mass movement dominates and seems to be primarily by solid-rock flow as in a large rock mass in the earth ad-

justing itself by movement under stress. In the earth the processes recognized are recrystallization, granulation and adjustment of granulated particles, gliding in crystals where possible, and shearing of various sorts. The summation of these individual movements and adjustments is movement of the mass in the direction of easiest relief.

In the glacier the original snow crystals of the névé have given rise to ice crystals, or ice granules. These are small and numerous in the beginning. As the ice moves down the valley they become larger and presumably fewer, favored ones apparently growing at the expense of others. Near the ends of certain large Alaskan glaciers granules have reached the size of baseballs. This growth of granules has been portrayed in detail by T. C. Chamberlin[4] and has been attributed to several factors. The pressure between adjacent granules is greater at some points than at others with the result that some melting occurs at the points of greatest pressure and the water refreezes in places of less compression. This involves not only a transfer of the material which was temporarily melted to places of lesser stress, but also by weakening the attachments between granules it permits more or less slipping or rotation of the granules themselves in adjustment to the stress conditions. This process of localized liquefaction will obviously be most active when the temperature of the mass of the ice is very near its melting point under the conditions of general pressure to which it is subjected. But somewhat similar results will also be obtained, though more slowly, under less favorable temperature conditions by a slow transfer of individual molecules (idiomolecular transfer) from points of greatest stress or greatest instability, to points of less stress or greater stability. In this transfer, as pointed out by T. C. Chamberlin, the smaller granules having sharper curvature of surface tend to lose more molecules and gain fewer than the larger granules of less sharply curving surface.[5] Consequently the larger granules grow at the expense of the smaller. These processes are to be compared with the recrystallization of rocks which plays such an important part in the solid-rock flow and

[4] T. C. Chamberlin and R. D. Salisbury, *Geology*, Vol. I (1904), pp. 294–301; (2d ed., 1909), pp. 308–16.

[5] Chamberlin and Salisbury, *op. cit.* (1904), p. 296.

folding of mountain building, and which results in more highly crystalline or metamorphic rocks.

These processes are essentially a yielding or accommodation of the crystalline units of the glacier or rock mass to the operating stresses. In the easement of stress the net result is a general movement of the mass in the direction of most ready relief which, in a valley glacier, is down the valley. Because of the large number of granules participating, very slight adjustments of the individual granules are capable of producing the forward motion observed in the mass. For example, it has been estimated that

> to account for a movement of three feet per day in a glacier six miles long, the mean motion of the average granule relative to its neighbor would be, roundly, 1/10,000 of its own diameter per day, or one diameter in 10,000 days; in other words it would *change its relation to its neighbors* to the extent of its diameter in about thirty years.[6]

But the individual granule adjustment is not limited to rotation; in addition there is slipping without rotation, slicing of granules, and movement of portions of crystals along gliding planes. Also surface waters freezing in cracks and pore spaces between granules exert forces aiding gravity in the general movement down the slope. In so far as there be a small amount of sodium chloride between granules, as urged by von Engeln,[7] such postulated salt would favor local melting and loosening of granular attachments, thus facilitating the adjustment and aiding in the basic process.

Ice moving by solid-rock flow in the manner outlined above not only maintains its crystallinity throughout, but the mass is capable of slowly changing in form to fit the valley mold into which it moves, of moving down the valley, and of folding locally where conditions favor this type of yielding. The word "plastic" is sometimes used for this behavior of the glacier, and used as if the name expressed a complete theory of glacier motion. Unfortunately the word "plastic" signifies little more than the familiar fact that the glacier moves *en masse* and maintains its continuity.

Shearing.—The middle portion of a valley glacier moves more rapidly than the lateral portions, and the top more rapidly than the

[6] *Ibid.*, pp. 299–300.

[7] "The Motion of Glaciers," *Science*, Vol. LXXX (1934), pp. 401–2.

bottom in consequence of greater resistance on the sides and bottom. Part of this differential motion is probably accomplished by the pervasive granular adjustment described above, but a study of the glacier surface shows that only a part takes place in this manner. Planes of shearing so oriented as to produce just such differential motion, as noted above, are very numerous. In the medial portion of the glacier these shearing planes dip upstream at moderate angles and along each of these the upper ice rides or has ridden forward over that beneath. No doubt, these do not all function at any given time, slippage apparently taking place actively along certain planes while others appear to be quiescent for the time being. Shearing along one of these active planes of the Glacier de la Brenva on Mont Blanc has been measured by an automatic-recording shear meter.[8] Near the sides of an alpine glacier hemmed in by valley walls, where the shear planes parallel the sides and are nearly vertical, slippage along these numerous planes gives a forward movement of the mass which is slowest at the glacier margins and becomes progressively more rapid toward the middle of the ice tongue.

The quantitative importance of the shearing in the general movement of the whole ice mass has not been determined. Along many planes the slippage may be slight; but along others it assumes the proportions of veritable thrust faults. Broken ends of bands of bluish ice which can be matched are found offset several feet. Much greater displacements there may also be, but in such cases the broken ends of bands can be matched with less certainty. The dragging of débris along shear planes, often for considerable distances, has already been noted. Slipping along the more important shear planes is of the type often called slice faulting in rock deformation. It is a movement of slices, or masses of crystalline material, with or without internal distortion.

Folding.—In many cases internal distortion is very evident where bands of débris, or of ice of different texture, are folded. For the most part this is the result of drag where part of the ice travels forward more rapidly than an adjoining part. If an upper portion of ice advances faster and farther than an underlying portion, layered

[8] Rollin T. Chamberlin, "Instrumental Studies on the Nature of Glacier Motion," *Jour. Geol.*, Vol. XXXVI (1928), p. 1–30.

structures, owing to resistance in front and below, may be bent into folds which become overturned and later may be drawn out into a recumbent position. The ice undergoes true rock folding. Differential movement of the ice in ground plan gives the curving, drawn-out pattern of surface moraines and to the peculiar "dirt bands" their sharp convexity downstream.

Crevassing.—Differential movement also tears the brittle ice into crevasses. As the middle portion moves farther in a given time than the sides, tensile stresses are developed along lines extending from the sides obliquely downstream. Tension in this direction on each side of the glacier causes fracturing, and pulling apart of the ice gives lateral crevasses which extend from the side of the glacier obliquely upstream for quite a distance toward the middle of the ice tongue. In the middle portion of the glacier, comprising in general rather more than half its width, the movement is more nearly uniform in ground plan though the surface moves faster than the ice below. Tension develops in the direction of movement and the crevasses form at right angles to the movement and transverse to the glacier. Where the glacier spreads out fan-like near its terminus, the ice splits under tension to produce longitudinal crevasses in the direction of ice movement and essentially normal to the ice margin.

Both flow and fracture.—Ice during its life in a glacier thus behaves like other rock undergoing deformation. It undergoes both rock flow and rock fracture. The processes of rock fracture are observed very generally in those portions of the ice exposed to view. But perhaps even more pervasive is rock flow. To some geologists rock fracture and rock flow seem sufficiently different and mutually exclusive as to necessitate their functioning only at different places or at the same place only when conditions there have been notably altered by erosion or other considerable changes. This belief finds expression in the postulated zone of fracture and zone of flow in the outer portion of the lithosphere. The concept of zones of fracture and flow has been carried over to glaciers, by postulating an upper frangible portion and a lower plastic portion.

ZONES OF FRACTURE AND FLOW

Several years ago the writer raised the question whether the postulated division of the outer part of the earth into a zone of fracture

and a zone of flow has not done more harm than good by picturing a sharp distinction which is not justified by the facts[9] and which, through rather general unqualified acceptance, has led to seemingly unfortunate conclusions in various different lines. Attention was called to the behavior of old tombstones and other rock slabs which, under the force of gravity during many decades, have slowly warped. This slow bending has taken place under a stress very small in comparison with the strength of the material as determined by building-stone tests. If this bending be by rock flow, as would seem to be the case, the postulated zone of flow in the earth would extend to the very surface of the earth, or, in the tombstone, above the surface. On the other hand, earthquakes, once supposed to originate only within a few miles of the earth's surface, are now known to have their origin also at depths of several hundred kilometers. "Focal depths of 200 to 300 kilometers are fairly common; and a focal depth as great as 700 kilometers has been observed."[10] If the strong earthquakes of deep origin be due to faulting like the strong ones from shallower depths, faulting would be extended many times deeper than the zone of fracture was supposed to reach.

What should be the nature of faulting at depths of several hundred kilometers, assuming that it does take place? Bailey Willis makes a distinction between fracturing and shearing, fracturing according to him involving some separation between the fracture surfaces.[11] Open fractures obviously cannot exist more than temporarily, and perhaps not even temporarily, at more than a very few miles below the earth's surface. Shearing, on the other hand, does not require separation and need not be so limited by depth. In thrust faulting it is shearing rather than fracture with separation which is essential. So, in a solid earth, we should recognize the possibility of faulting at considerable depths.

If these considerations be valid, the so-called zone of flow should reach to the surface of the earth, for the tombstones show that rocks

[9] "The Zone of Cavities and the Zone of Continuity," *loc. cit.*, pp. 194–95.

[10] G. J. Brunner and J. B. Macelwane, *The Brunner Focal Depth-Time-Distance Chart* (John Wiley & Sons, 1935).

[11] Bailey Willis and Robin Willis, *Geologic Structures* (3d ed.; New York: McGraw-Hill Book Co., 1934), p. 17.

there may "change in form without conspicuous fracture" and the zone of shearing and faulting perhaps does not terminate short of many scores of miles below the surface. In any case there is such a great overlapping of these zones that their supposed distinctiveness vanishes.[12] If, however, by zone of fracture one means nothing more than a "zone of cavities" contrasted with a "zone of continuity" below, that is a different matter.

GENERAL CONSIDERATIONS

In glaciers, as in the earth, it is natural to suppose that jointing, faulting, and shearing which involve the moving of considerable masses with respect to one another should take place most readily near the surface where the resistance to the movement of large masses as units is least. With increasing depth it is natural to expect less movement of large aggregates as separate units, and relatively more disseminated movement by minute adjustments between small units, or rock flow. Probably tension jointing and crevassing, which involve open fracturing, diminish more rapidly with increasing depth than thrust faulting and shearing under compression. Perhaps in a thick glacier jointing may die out altogether before the bottom is reached. But need we suppose that shearing under compression cannot take place in the basal portion of even the thickest of existing valley glaciers? The writer does not think so.

In the other direction, is the general glacier movement by granular adjustment, or rock flow, to be limited to the more deeply buried portion of the ice in a postulated zone of flow? This seems very unlikely. It is hard for the writer to believe that in a glacier tongue moving down a steep slope there is no adjustment between granules even at the very surface of the ice. Though much shearing takes place between aggregates of granules this in no wise precludes intergranular adjustment as well. The two are not mutually exclusive, though the shearing, by easing the stresses, reduces the amount of other adjustment required.

It is sometimes assumed that glacier ice which shows evidence of having undergone both flowage and faulting "flowed" while deep

[12] C. K. Leith long ago approached these conclusions by recognizing an intermediate zone of combined fracture and flow and stating that perhaps the geologist never sees rocks which have been in the zone of complete solid-rock flow.

within the glacier and faulted later in a zone of fracture as it approached the surface by ablation. Against this assumption may be cited the fact that it is customary to find old shear planes both faulted and folded. Is it necessary to suppose that such shear planes were formed near the surface of the glacier and later depressed deep below the surface to be folded in a zone of flow and then brought to the surface again to be seen? Ice folds have been noted on the sides of Greenland glaciers so related to visible rock embossments over which the glacier is moving[13] as to leave little doubt that the folding was genetically related to the embossment and has recently taken place not far from where observed. In the earth, faults pass into folds upward, downward, and laterally. Consequently it seems to the writer that we should get away from the zonal concept and recognize that both folding and faulting can take place in the same part of a glacier under varying conditions of stress and temperature.

Under moderate stresses the ice may slowly move and change in shape by solid-rock flow; under relatively rapid and sufficiently great increments of stress, it may shear and fault. Not only does the nature of the stress determine the kind of deformation, but the nature and condition of the material are also determining factors. In the earth, movement of large masses as units, without internal distortion or with internal distortion subordinate, is associated with relatively competent rocks, and the distributed movement by adjustment of minute units is most characteristic of relatively incompetent rocks. For example, a strong, brittle limestone formation is likely to exhibit more faulting and less folding than an adjoining weak clayey shale, though each formation will probably show both folding and faulting. Differences in the competency of rock strata are, to a considerable extent, due to differences in chemical and mineral composition, but glacier ice is more uniform. Glacier ice, however, does vary in competency with the temperature, particularly because its temperature is frequently close to the melting point. Adjustment between glacier granules naturally takes place most readily and rapidly when the temperature of the ice is at or near the melting point. The ice is then relatively incompetent and moves

[13] T. C. Chamberlin, "Recent Glacial Studies in Greenland," *Geol. Soc. Amer. Bull.* 6 (1895), p. 208.

easily. A familiar fact is that glaciers move most rapidly in hot weather when melting is at a maximum. In very cold weather the the surficial ice of a glacier yields less readily by internal adjustment and is more competent than at a higher temperature. It is, however, distinctly brittle. Increase in competency allows accumulation of more differential stress before yielding takes place and this should favor fracture relative to flow. On the other hand, the glacier moves more slowly in cold weather than in warm weather and resulting local stress differences within the ice should be correspondingly slower in development. The slower the rise of differential stress the less the likelihood of fracture in deformation. Here are two opposing factors whose quantitative importance has not been adequately investigated.

More quantitative studies of the behavior of glacier ice under varying conditions are necessary before we can have an adequate understanding of the nature of glacier movements. But pending such information, we can at least be certain that such movements are composite and complex. Our concepts, for the most part, have been too simple, as they also have been for many other geologic processes. Processes intertwine and overlap and their relative importance changes with changing conditions. To advocate either a "plastic theory of glacier motion," or to believe that the geologist who recognizes shearing as an important factor must perforce advocate a "shear theory," is to seize upon only a part instead of the whole and to have but a very imperfect understanding of the actual composite phenomenon. The plastic theory is little more than a name for the familiar fact that glaciers move *en masse* and change in shape. The so-called "shear theory," if it *were* urged by those who have studied shearing in glaciers, would imply belief that shearing is the *only* process producing glacier motion. A complicated phenomenon like glacier movement should be considered as a combination of processes, each contributing its own part and special features. The discovery that a particular process is in operation does not signify that that is the whole story. Unfortunately this has been all too commonly overlooked in scientific investigations.

REVIEWS

The Fiord Region of East Greenland. By LOUISE A. BOYD, with contributions by J HARLEN BRETZ, O. M. MILLER, WALTER A. WOOD, WILLIAM B. DREW, CHARLES B. HITCHCOCK, and JOHN K. WRIGHT. American Geographical Society Special Publication 18. New York: The Society, 1935. Pp. x+369; figs. 363; pls. 14. $4.00.

This sumptuous publication is the outcome of the two East Greenland summer expeditions by Miss Boyd undertaken in the "Veslekari" in 1931 and 1933. The last mentioned was provided with somewhat exceptional equipment, which included echo-sounding apparatus and the most modern of photogrammatical and photographic outfits. The scientific staff consisted of well-trained men and included, in addition to those who contributed to the volume, Mr. N. E. Odell as geologist. The area studied is that of the Franz Josef and King Oscar fiord region outlined roughly by the parallels of 72° and 74° N. and the meridians of 22° and 27° W. The more detailed mapping operations were concentrated within a relatively small area in Fraenkel Land. The report includes narrative and photographs by Miss Boyd, physiographic studies and photographs by Bretz, photogrammatical work by Miller and Wood, botanical work by Drew, echo-sounding by Hitchcock, tide records by Miller, and description of the vessel and its equipment by Miss Boyd. In addition, there is a historical outline of exploration within the region by John K. Wright, of the American Geographical Society.

The outstanding feature of the publication is the excellent photographs which are reproduced in the most lavish way (considerably more than half the pages are pictures), and these are well fixed as to position by their legends. Of great value, also, are the soundings within the fiords, which are arranged in definite longitudinal and transverse profiles, well determined as to position. The work is a valuable contribution to the geography of this interesting region.

W. H. HOBBS

"The Story of Arctic Voyages and Exploration," by JOHN MATHIESON, in *Scottish Geographic Magazine*, Vol. L, No. 5 (1934), pp. 281–308. Map.

Within this brief compass of twenty-seven pages of text, there is included in chronological order an excellent outline of arctic voyages and exploration that is remarkable for its comprehensiveness as well as for its accuracy. It is accompanied by a great map in color, giving the routes of explorers and also showing land elevation and sea depth.

W. H. HOBBS

To the North, the Story of Arctic Exploration from Earliest Times to the Present. By JEANNETTE MIRSKY. With Introduction by V. STEFANSSON. New York: Viking Press, 1934. Pp. xx+386. $3.75.

Quite in contrast to the outline by Mathieson, this book is a detailed account of arctic work, also from the earliest times, For the earlier part, the book has been well done; and it can perhaps be said to be the equal of any work of its class. This is not true of the later third of the book, which concerns our own times. This portion gives the impression that the author had tired of her work before it was finished, and the grasp displayed in the earlier portion is lacking. The most important arctic expedition of recent time, that of Wegener in 1930–31, was apparently quite forgotten and is introduced as a brief footnote, which states quite incorrectly that the leader and "two" Greenlanders were "killed" on their return from the central station. A most one-sided position is taken in assessing the blame for failure of the disastrous Greely expedition. The faker, Cook, is treated quite seriously, and his portrait is coupled with that of Peary. In her efforts to prove that Peary was careless in his mapping, the south coast of Independence Fiord in northeast Greenland is represented on a crude map (p. 260), in which the trend of this stretch of coast is twice as far from the correct position as that originally sketched by Peary, and it is made more than twice as long. Contrary to the attitude of Danish authorities generally, the tragic loss of the leader of the Danish Northeast Greenland Expedition in 1906–8 is laid at Peary's door, because the deep depression which separates Peary Land from the icecap of Greenland was represented on his maps (dotted) as a channel.

The maps almost throughout, with the exception of the colored plate at the end, are quite crude. A minor, though important, error in drawing

the colored plate is the failure to represent Bellot Strait. Von Gronau is declared (p. 352) to have been the first to fly across the Greenland icecap, though this honor belongs to the American flyer, Parker Cramer, who had preceded Von Gronau by about a month. The five Greenland expeditions of the University of Michigan find no mention whatever in the text. Yet with all these errors and omissions which relate to the later portion of the book, it has considerable value and will, in the earlier portion, be useful for reference.

W. H. HOBBS

"The Geology of Parts of Southern Norway," by OLAF HOLTEDAHL, ARNE BUGGE, CARL F. KOLDERUP, HALVOR ROSENDAHL, JAKOB SCHETELIG, and LEIF STORMER, in *Proceedings of the Geologists' Association*, Vol. XLV, Part III (1934), pp. 307–88. London: Geologists' Association, 1934.

Under this title are brought together a group of papers prepared for the Summer Field Meeting of the Association held in 1934. They treat principally of the region centering around Oslo and give in condensed form the main features of the geology of that very interesting area.

R. T. C.

Geology and Mineral Resources of the Hammond, Antwerp, and Lowville Quadrangles. By A. F. BUDDINGTON, with a chapter on "The Paleozoic Rocks of the Lowville Quadrangle" by RUDOLF RUEDEMANN. New York State Museum Bulletin 296. Albany: University of the State of New York, 1934. Pp. 251; figs. 54; maps 4. $2.50.

The bedrock underlying these areas along the western and northwestern border of the Adirondack Mountains comprises the Grenville metamorphic series, various later igneous intrusions of pre-Cambrian age, and relatively flat-lying Cambrian and Ordovician sandstones and limestones. The foliation of the Grenville, essentially parallel to the bedding, is attributed to recrystallization, injection, permeation, and replacement by vapors and solutions from the intrusion of granitic and syenitic magmas which occurred simultaneously with orogenic folding. Under such conditions a slaty cleavage across the bedding, such as forms in shales during strong folding, would not necessarily be expected.

The invading magmas were, for the most part, forced in along the bed-

ding planes of the Grenville sediments, spreading them apart, disrupting the more brittle members, stretching the more plastic layers, and in part dissolving and replacing them. Most of the intrusive masses have a sill or sheet structure, but particularly striking are the granite phacoliths intruded along the crests of folds during the deformation of the Grenville formations. At least two series of intrusive rocks occur—an older group, including gabbro, diorite, and quartz-diorite; and a younger group, including syenite, quartz-syenite, and granite. It is possible that all the magmas were intruded during one epoch; but if so, this period must have been very long and the intrusions at successive intervals.

The report is a thorough and able piece of work. More space is naturally given to the complex pre-Cambrian rocks and their difficult problems than to the relatively simple Paleozoic and later formations. The mineral resources do not require elaborate treatment.

R. T. C.

Geology of the Potsdam Quadrangle. By JOHN CALVIN REED. New York State Museum Bulletin 297. Albany: University of the State of New York, 1934. Pp. 98; figs. 60; maps 2. $0.75.

This bulletin follows the same general lines as *Bulletin 296*, but the treatment is simpler and more largely descriptive. For fuller discussion of the problems of the pre-Cambrian, the reader is referred to the preceding bulletin by Buddington.

R. T. C.

Laboratory Manual for General Geology. By MARK HOWARD SECRIST. New York: Macmillan Co., 1935. Pp. 302; figs. 52; pls. 15. $1.75.

This manual embodies another attempt to write a guide for laboratory work in elementary geology—an admittedly difficult and, in the reviewer's opinion, a yet unsolved task. The book is in the main conventional, though the chapter on "Block Diagrams" is new. While the latter is both novel and interesting, it smacks somewhat of busiwork.

More than two-thirds of all the pages in this manual are blank pages on which the student is expected to write out the results of his studies and the answers to the sets of questions appended to each exercise. It is the reviewer's opinion that the questions on topographic maps are too generalized for elementary students and that they need to be more specific,

and that the questions dealing with paleontology cannot in many cases be answered from the laboratory work given. The work entitled "Regional and Historical Geology" is hardly either one or the other. Work is given neither on the pre-Cambrian (except as it is incidentally included in the study of one or two folios) nor on the Canadian shield as a region. To omit either results in a decidedly unbalanced presentation.

F. J. PETTIJOHN

Geology of the Western San Gabriel Mountains of California. By WILLIAM J. MILLER. "Publications of the University of California at Los Angeles in Mathematical and Physical Sciences," Vol. I. Berkeley: University of California Press, 1934. Pp. 114; pls. 13; figs. 6; map 1. $1.50.

The San Gabriel Mountains are a great uplifted fault block, bounded on the south by the Sierra Madre and associated faults, on the northeast by the San Andreas, and on the northwest by the Soledad and related faults. The pre-Cretaceous rocks, which constitute the main mountain mass, are typical plutonics, together with metamorphosed plutonics and sedimentaries and some altered volcanics. They fall into two groups: an older one of probable pre-Cambrian age, and a later succession of late Jurassic intrusives related to the Sierra Nevada orogeny. The mountain mass was a positive area throughout Tertiary time, and its erosion gave rise to very thick clastic deposits on its flanks. At the beginning of the Quaternary, faulting, accompanied by folding of the adjacent Tertiary strata, raised the present mountain block.

Particular attention naturally has been given to the intrusive rocks, owing to their dominant importance. Of especial interest is the anorthosite series, which occupies large areas in these mountains. The anorthosite, including its gabbro-diorite facies, is a true intrusive having the shape of either an asymmetric, thickset laccolith or an asymmetric batholith increasing in width upward. The author believes that the original magma from which the facies of anorthosite were derived was gabbro-diorite, this being about the average composition of all the facies. He gives reasons for thinking that the original magma differentiated irregularly at a greater or less depth below the present position of the facies and that this was followed by more or less movement before final consolidation.

R. T. C.

"The Architectual, Structural, and Monumental Stones of Minnesota," by GEORGE A. THIEL and CARL E. DUTTON, in *Minnesota Geological Survey Bulletin 25*. Minneapolis: University of Minnesota Press, 1935. Pp. 160; figs. 78; pls. 12. $2.50.

This bulletin supplements *U.S. Geological Survey Bulletin 663* (1918) in presenting the merits of the various structural and ornamental stones quarried and fabricated in Minnesota. Since 1918 new quarries have been opened, new varieties of stone have been found, and new methods of quarrying and fabricating have been developed. Since the geology was fully treated in the earlier bulletin, the major portion of this report is devoted to description of the present products, places and methods of production. The numerous illustrations, especially the twelve colored plates of the most important granites and dolomites, add greatly to the value of the bulletin.

GORDON RITTENHOUSE

"Kyanite and Vermiculite Deposits of Georgia," by LOUIS M. PRINDLE and others, in *Geological Survey of Georgia Bulletin 46*. Atlanta: Stein Printing Co., 1935. Pp. 50; figs. 4; pls. 11.

A survey of the kyanite reserves of Georgia conducted during the summer of 1934 by the U.S. Geological Survey in co-operation with the Georgia Division of Geology led to the discovery of wide areas of a kyanite-bearing mica-schist and isolated areas of kyanite in other forms and occurrences, such as dornicks, placers, and in quartzite. The kyanite is found in the Piedmont area, which is bounded by the Fall line to the south and the Cartersville fault to the northwest. The average kyanite of the schists contains about 3 per cent iron and 3 per cent silica, but the placers yield a product containing only about 1 per cent iron. The Bureau of Mines is conducting experiments upon the beneficiation of the schist material and predicts that the kyanite can be recovered and used when there is sufficient demand.

R. T. C.

Earth, Radio, and the Stars. By HARLAN TRUE STETSON. New York: McGraw-Hill Book Co., 1934. Pp. xvii+336, figs. 88+frontispiece. $3.00.

In this volume the author introduces the new science of cosmecology, the study of the earth in relation to the cosmic scheme in which it is placed. In its broadest sense the science deals with problems of terrestrial physics—problems that concern geologists, physicists, astronomers, and others.

In the first chapters of his book Dr. Stetson reviews the astronomical relations of the earth. Then follow chapters on the stability of the earth's crust, the interior structure of the earth, and the influence of tides on earth economy.

A series of several chapters traces the influence of the sun on the earth and human affairs. Sun spots and their variations are treated in some detail. With the variation in sun spots are compared the variations in the earth's magnetism and in radio reception, showing the close interdependence of apparently unrelated fields. Interrelations between radio and the moon's phases, radio and meteors, radio and solar eclipses, indicate the extent to which the author covers his subject. Radio thus becomes an important instrument of research in this wide field of cosmecology. Nocturnal illuminations, such as aurora borealis, are touched upon, and finally cosmic rays themselves receive attention. A summary of the broader aspects of cosmecology closes the volume.

The book is well written and clearly illustrated. It deserves the close attention of geologists interested in the structure and physical behavior of the earth, as well as those concerned with an integration of geology with the other sciences.

W. C. KRUMBEIN

Handbuch der Geophysik. Edited by B. GUTENBERG. Volume I, Part II. Berlin: Bornträger, 1933. Pp. v+191; figs. 34. Rm. 30; by subscription Rm. 24.

The present publication represents an addition to the already imposing list of volumes and parts of the *Handbuch* that have been published to date. As part of Volume I this section continues a discussion of the earth as a planet. Part I, already issued, covers the origin of the solar system, the figure of the earth, and other physical aspects. The second part, reviewed here, supplements these articles with four others of an astronomical nature.

The first section is on tidal forces, by J. Bartel. The author develops tidal theory in full detail, and includes a section on harmonic analysis. The second section of the book, by F. Hopfner, carries on the work by treating earth tides in an equally exhaustive manner. The third and fourth sections are by M. Milankovitch. They include an analysis of such earth movements as precession and nutation, and a full consideration of the theories of pole wandering. At the end of the last section is an admirable summary which briefly reviews the more mathematical treatment in the text.

The book is well printed and clearly illustrated. This entire set of volumes, it has been pointed out before, belongs in every geological library. As a reference work it has no equal in its field.

W. C. KRUMBEIN

Vom wachsenden Erdball. By O. C. HILGENBERG. Berlin: published by the author, 1933. Pp. 56; figs. 28+map and insert.

In this small and compact volume the author offers a theory of a growing earth that at first glance is quite startling. Instead of the generally accepted notion of an earth shrinking through time he postulates an earth which is growing at an exponential rate—slow at first and more rapidly as time goes on. The present continents are pictured as the broken pieces of an original skin of the earth, firmly fastened to a globe of about half the present radius of the earth, a *Shelfkugel* of pre-Cambrian times. During growth this skin became disrupted and the present continents were brought into being.

Among the difficulties which the author had to face in fitting the continents into an original earth-skin is that it was necessary to divide North America diagonally from Alaska to Florida. His reconciliation by means of faulting of the continental block is at least ingenious, and he marshals an impressive array of evidence in support of his ideas. The theories which Hilgenberg advances for the growth of the earth appear to involve a transformation of ether into matter—a question that must concern theoretical physicists rather than geologists.

It is impossible to do justice to Hilgenberg's ideas in a review. The style of writing is interesting and entertaining, and to aid the reader in visualizing his *Shelfkugel* an insert which may be removed and pasted on a ball of about 3 inches diameter is included in the book. With this small model the changes that he postulates may easily be followed. Further, the volume is fully illustrated with half-tones of globes in various stages of growth, showing the earth toward the close of pre-Cambrian, during Jurassic times, at the beginning of the Cenozoic, and at present.

Unfortunately, the reviewer believes that several difficulties will militate against the general acceptance of Hilgenberg's theories. Nevertheless, he recommends the book to the attention of geologists for its refreshing point of view, and for the masterful way in which the author marshals his evidence and points his arguments. Certainly, the volume is a challenge to the easy acceptance of current notions by showing the possibility of quite another state of affairs.

W. C. KRUMBEIN